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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS 02139

NON-LINEAR MATERIAL THREE DEGREE OF FREEDOM ANALYSIS OF SUBMARINE DRYDOCK BLOCKING SYSTEMS

by

LIEUTENANT COMMANDER RICHARD DANIEL HEPBURN, USN

COURSE XIII-A
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NON-LINEAR MATERIAL THREE DEGREE OF FREEDOM ANALYSIS OF SUBMARINE DRYDOCK BLOCKING SYSTEMS

by

LIEUTENANT COMMANDER RICHARD DANIEL HEPBURN, U.S. NAVY

B.S. Ocean Engineering
U.S. Naval Academy (1976)

SUBMITTED TO THE DEPARTMENT OF OCEAN ENGINEERING
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NON-LINEAR MATERIAL THREE DEGREE OF FREEDOM ANALYSIS OF SUBMARINE DRYDOCK BLOCKING SYSTEMS

by

LIEUTENANT COMMANDER RICHARD DANIEL HEPBURN, U.S. NAVY

Submitted to the Department of Ocean Engineering in partial
fulfillment of the requirements for the degrees of Naval
Engineer and Master of Science in Naval Architecture and
Marine Engineering.

ABSTRACT

U.S. Naval shipyards where submarines are drydocked are located in regions of the United States where significant earthquakes are known to occur. The graving dry docks at these shipyards are currently designed to withstand earthquake accelerations up to 0.26 g's. This thesis develops a non-linear material model for wood drydock block caps which more closely represents its actual behavior than linear elastic material models used previously. Using this non-linear model, it is determined that submarine drydock blocking systems would fail at even lower earthquake accelerations than that predicted by linear material models. This confirms that submarine drydock blocking systems would fail at accelerations which are significantly lower than the Navy's 0.2 g survival requirement.

New blocking materials are then analyzed using non-linear models developed in this thesis in order to determine their potential for increasing system survivability. The materials analyzed are natural rubber and dynamic isolators. It is determined that when these materials are incorporated in the blocking systems,significant increases in survivability occur; however, all the systems still fail well below the required 0.2 g level. This thesis makes it clear that the current submarine drydock blocking systems provide inadequate protection of the submarines from accelerations caused by highly probable earthquakes, but the use of new blocking materials can reduce the risk of blocking failure.

THESIS SUPERVISOR: Dale G. Karr, Ph.D.

TITLE: Associate Professor of Ocean Engineering

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BIOGRAPHICAL NOTE

The author graduated from the United States Naval Academy with a Bachelor of Science Degree in Ocean Engineering in 1976. He served aboard the *USS Meyerkord* (FF-1058) as the Damage Control Assistant and Main Propulsion Assistant from 1977 to 1980. At Long Beach Naval Shipyard from 1981 to 1985, he first served as a ship superintendent for the overhauls of the *USS Kinkaid* (DD-965), *USS Tarawa* (LHA-1), and *USS Gridley* (CG-21). He then served as the shipyard Docking Officer for two and half years and drydocked many ships including the *USS Missouri* (BB-63). Finally, he served as the shipyard Production Engineering Officer before reporting to M.I.T. in June 1985.

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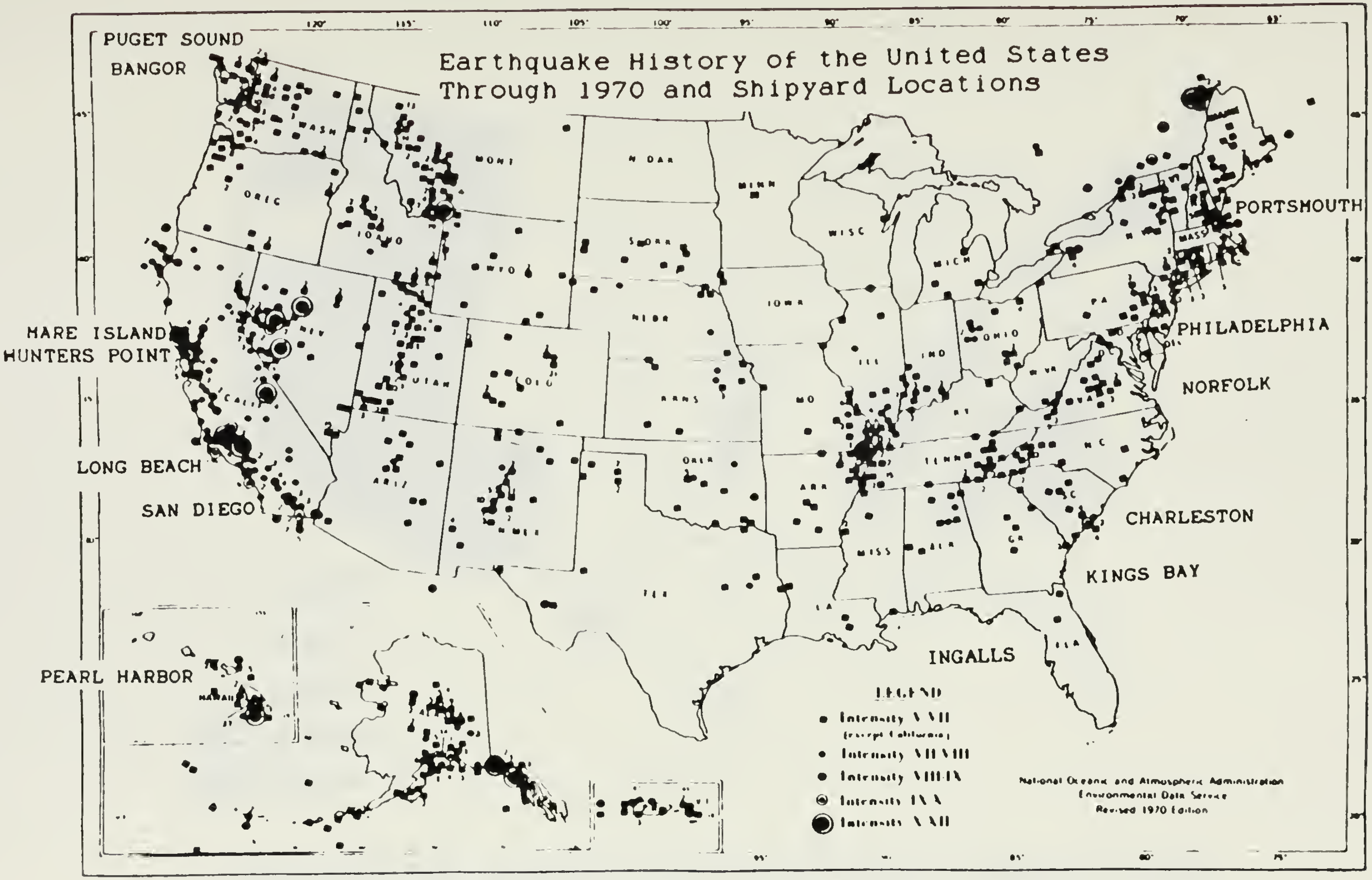
Chapter 1

INTRODUCTION AND DESCRIPTION OF THE EARTHQUAKE THREAT TO SUBMARINE DRY DOCK LOCATIONS

1.0 Introduction

Currently submarines are routinely drydocked in graving docks at three locations on the west coast and five locations on the east coast of the United States. In addition they are drydocked in graving docks in Pearl Harbor, Hawaii. They also can be docked in graving docks and shiplift systems at many additional locations on both coasts if required. Graving docks are docks which have been dug out of the ground. Shiplift systems lift ships out of the water where they are then transported on a carriage assembly to a land based position. When a submarine is in one of these docks it is susceptible to any ground motion that may occur. Figure (1.1) [1] illustrates the locations where submarines can be placed in graving docks. This figure also indicates where earthquakes have historically occurred.

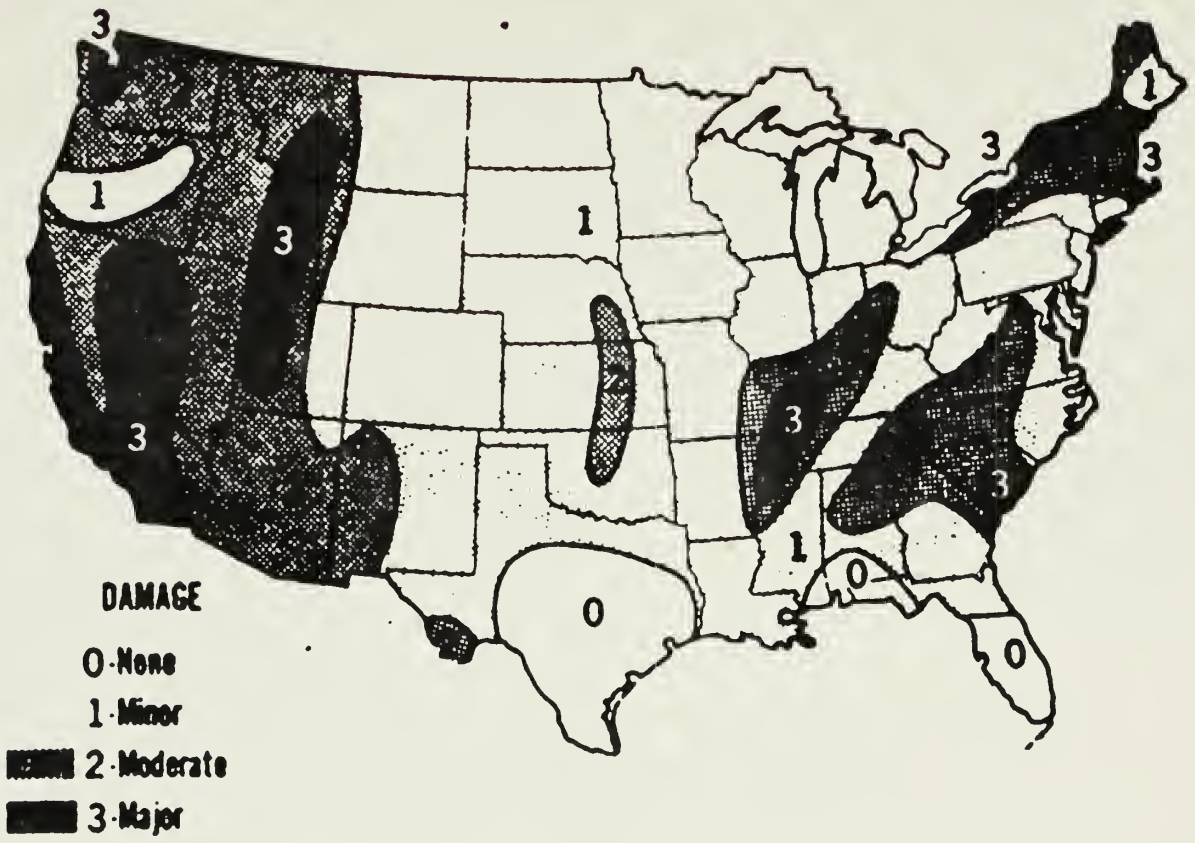
Shipyards, by their nature, need to be located along the coast. Unfortunately the locations of the west coast shipyards coincides with the areas of highest earthquake risk. Even on the east coast, earthquakes of significant magnitude have been known to occur where submarines now are drydocked.



Earthquake History of the United States Through 1970 and Shipyard Locations

Earthquakes (intensity V and above) in the United States through 1970

FIGURE 1.1



Seismic risk map for conterminous United States.

FIGURE 1.2

Figure (1.2) [1] indicates the areas in the United States most susceptible to earthquakes. On the east coast, Portsmouth Naval Shipyard and Charleston Naval Shipyard are located in the highest risk zones.

1.1 Dry Dock Seismic Vulnerability

1.1.1 San Francisco Area

Mare Island Naval Shipyard is a submarine repair shipyard located on the northern tip of San Francisco Bay. The Bay itself was created by the motion of the San Andreas fault. San Francisco was built on this fault. The city experienced a devastating earthquake on April 18th 1906. 700 people died in this earthquake. Just south of San Francisco, the fault shifted 16 feet in one minute [2]. This magnitude 8.3 earthquake was one of greatest known shocks in California [1]. It was associated with the largest known length of slip (21 feet) along a fault plane in the contiguous United States. The damage was unevenly distributed due to subsurface conditions [1]. Chimneys remained standing which were mounted on rock. Buildings further away from the epicenter collapsed because they were constructed on land fill. Mare Island Naval Shipyard is also built on land fill.

On April 24th 1984 a 6.2 magnitude earthquake occurred at Morgan Hill, California which is about 45 miles south of Mare Island Naval Shipyard. It was the consequence of a sudden rupture along a 30 km segment of the historically active Calaveras fault. This was the third damaging earthquake to strike the San Francisco Bay region since 1979, and the largest event in the region since 1911. It produced many significant records of ground and structural shaking including the largest horizontal ground acceleration (1.29 g) ever recorded [3].

Six potential nuclear power plant locations were abandoned along the California coast due to their proximity to fault locations and vulnerability to earthquake motions [2]. However, nuclear powered ships are still drydocked in areas susceptible to earthquakes. Hunters Point in San Francisco is still used to drydock nuclear powered surface ships. It is located within 12 miles of the San Andreas fault.

1.1.2 Southern California Area

Long Beach Naval Shipyard is also located in an extremely vulnerable area. Long Beach, California experienced a major earthquake on March 10, 1933 seven years before the construction of the shipyard at Terminal Island. This earthquake measured 6.3 on the Richter Scale and caused

considerable damage and loss of life. The major destruction was in the thickly settled district from Long Beach to the industrial section south of Los Angeles where water-soaked alluvium and other unfavorable geological conditions combined with the presence of much poor structural work to increase the damage [1].

Since Long Beach Naval Shipyard was built, the ground in the shipyard has subsided over 20 feet due to oil being pumped out from the ground beneath the shipyard. The shipyard is located primarily on land fill which is known to be tremendously susceptible to earthquake damage. On October 1st 1987 an earthquake hit Whittier, California which is approximately 20 miles northeast of Long Beach. Initial reports indicated that this earthquake had a magnitude of 6.1 on the Richter Scale [4],[5], but was later downgraded to 5.9 [6]. Six people were killed and over 100 injuries were reported. Eight to ten buildings collapsed, hundreds of homes were damaged, and many buildings were declared unsafe. Local officials stated that most of the buildings that experienced damage were 30 to 40 years old and did not meet modern earthquake resistant structural requirements. Eyewitnesses indicated that the ground appeared to move back and forth up to two feet [2].

Long Beach Naval Shipyard had accelerographs located in graving dry docks 1 and 2. These devices all produced acceleration time histories for this earthquake. Significant motion was felt in the shipyard. The cruiser USS Leahy, which was in dry dock # 3, experienced side block shifting during the earthquake.

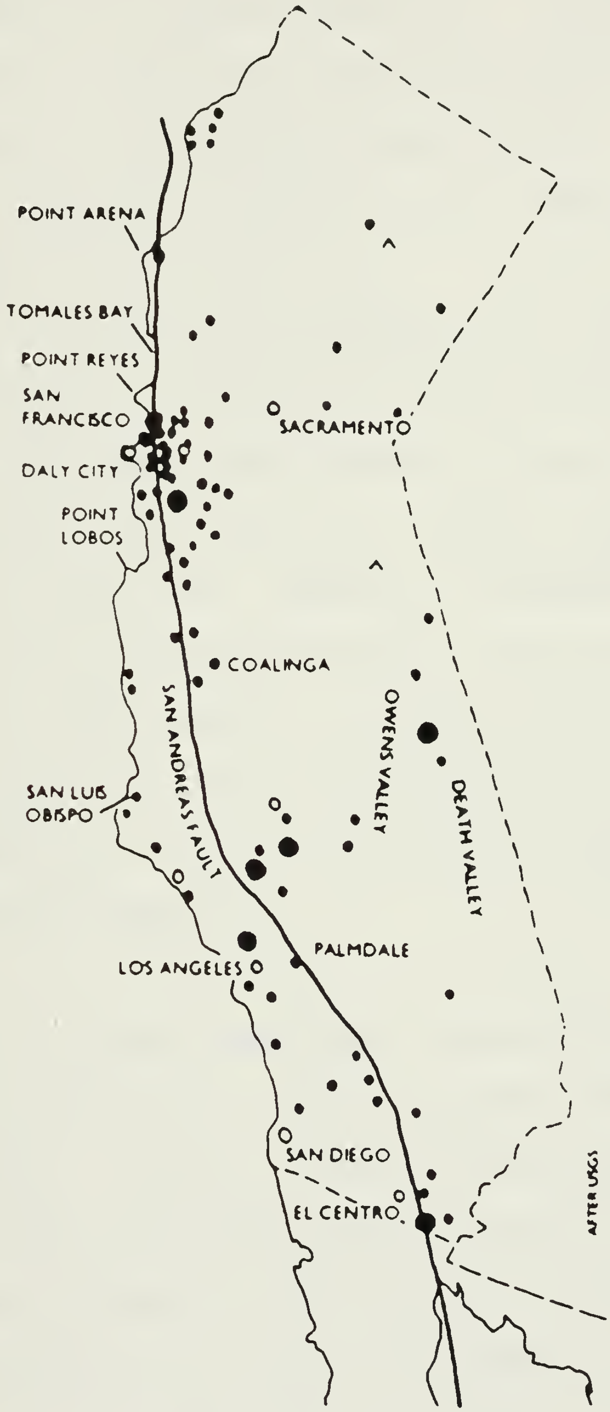
At least sixteen aftershocks occurred measuring greater than 3.0 near the epicenter within three hours. Major sections of freeway were closed due to structural cracks. 250,000 businesses and homes were without power after the earthquake. Over 100 strong motion records were made of the 1 October 1987 Whittier earthquake [7]. The largest ground acceleration measured was .45 g horizontal at 10 km from epicenter. The area south of the quake had relatively low shaking (0.2 g) though only 10 km from the epicenter. Many more distant stations had greater amplitudes.

Other areas in the United States which have graving docks and shiplift systems are vulnerable to earthquakes as is discussed in section 1.3.

1.2 California's Earthquake Potential

The Whittier earthquake epicenter was not located on the San Andreas fault but rather on the smaller Elsenor fault [8]. The San Andreas fault, figure (1.3) [9], is 650 miles long and 20 to 30 miles deep. The PBS series "The Making of a Continent" [2] describes the current geological events occurring on the west coast of the United States. The cause of the earthquakes in that region is due to the location of the coastal areas of California over a spreading center. This is causing the area to the west of the San Andreas fault to gradually shift northward relative to the rest of the continent. Earthquakes occur when this movement is resisted and slippage occurs along the fault. The magnitude of the earthquakes is proportional to the amount of slippage that occurs along the fault. The more time between fault slippage in a particular region the more strain energy is stored and the longer the fault slips when the break finally occurs. This geological scale "stick slip phenomena" causes devastating earthquakes.

The western portion of California from San Francisco Bay to the northern tip of the Gulf of California is on the Pacific Plate. This plate is moving northward at a rate of two inches per year relative to the North American plate along the San Andreas fault. There are many other faults in addition to this major fault in this region.



THE SAN ANDREAS FAULT

FIGURE 1.3

Areas in California which experience continuous small earthquakes may be in a safer condition. In the center of the San Andreas fault, the plates slip smoothly by each other at 3.5 cm's annually triggering no major quakes. But north and south of this region of "creep" plate edges are stalled, locked together by friction [10]. It is currently the southern portion of the San Andreas fault that is considered the most vulnerable to producing a major quake. Currently in an area along the fault near Palmdale, California approximate 13 feet of movement is stored up. When an earthquake occurs in this location and this energy is released, it will be on the order of 8.3 on the Richter Scale. This is the portion of the San Andreas fault which scientists have determined has a frequency of major earthquake occurrence of every 145 years. This earthquake will have the equivalent energy release of a 50 megaton hydrogen bomb [2].

The 1940 El Centro earthquake which had a magnitude of 7.1 on the Richter Scale actually shifted the United States border with Mexico 14'10". Parts of the San Andreas fault near Palm Springs, California have built up as much as 36 feet of stored strain energy. This portion of the fault has an earthquake frequency of one every 500 years [2].

According to a special report by the Emergency Task Force of the California Division of Mines and Geology certain areas of the Los Angeles basin are more vulnerable than others to the effects of a 8.3 magnitude earthquake with an epicenter near Palmdale [2]. Specifically, the cities of Santa Ana and Long Beach have very high potential for ground failure. The ground can behave like quicksand causing catastrophic damage to buildings even though they are 50 miles from the epicenter. Scientists believe that an earthquake of this magnitude in the Los Angeles area will cause "the greatest disaster in the United States since the Civil War" [2].

A Federal Emergency Management Agency Report scenario predicts that 3000 to 14000 people would be killed and 200,000 people would be left homeless in such an earthquake. There would be locally extensive damage to highways. Bridges and power lines would fall. Two of three main water aqueducts would be severed for six months [2].

The 1 October 1987 Whittier earthquake did nothing to relieve the pressure along the San Andreas fault . Dr. Bruce Bolt [8], a seismologist at the University of California at Berkeley said that the Whittier earthquake caused no change in the energy "locked in the rocks" of the San Andreas fault. He said "the Big One will come in the next twenty years".

PBS in December 1987 broadcast a documentary on the potential hazards of the San Andreas Fault. In that broadcast they mentioned that through carbon dating scientists can determine the frequency of past earthquakes. At a point along the San Andreas fault in Southern California, the fault was excavated and the past fault shifts examined. It was determined that the approximate frequency of major earthquakes on the southern portion of the this fault was 145 years. The last major earthquake to occur in this region was in 1857 (Ft. Tejon Earthquake). This earthquake occurred 125 years ago. Scientists feel that there is a very a good chance for another major earthquake to occur in this area in our lifetime. This same program quoted Mr. Alex Cunningham, Director of the California Office of Emergency Services, as saying "It is not a question of if but when the great earthquake will occur in Southern California." Mr. Cunningham stated that this earthquake in the Los Angeles region could occur tomorrow or any time in next 30 years.

The "Big One" is predicted to have a magnitude of about 8.3 on the Richter scale. This will be 800 times larger than the earthquake experienced in San Fernando in 1971. When the last major earthquake hit the Los Angeles area in 1857 only 11,000 people lived there. In 1988, well over 24 million people live in the Los Angeles region. The PBS program stated that a major earthquake in Los Angeles would be "a natural disaster without precedent in American history."

During the February 9th 1971 San Fernando, California earthquake 65 people died and there was more than $500 million in damage in the Los Angeles area. The earthquake registered 6.4 on the Richter scale. There have been more that 4000 earthquakes in California since 1900. Eight earthquakes greater than 5.0 on the Richter scale have occurred in California in 1987 alone. Since the 1971 earthquake, freeway overpasses have been strengthened, building simulation studies conducted, and buildings such as the San Bernardino County building constructed on rubber isolators. Richard Eisner of the California Department of Emergency Services said it will take decades to strengthen the old buildings in the Los Angeles area so they can resist earthquake motion.

According to the U.S. Geological Survey [1], the San Fernando earthquake injured over 2000 people. Thousands of homes and businesses sustained appreciable damage and hundreds of them had to be abandoned. 174 aftershocks of magnitude 3.0 or greater were recorded. Two of these shocks were magnitude 5.8. The record from the main shock revealed the highest acceleration ever measured to date (1.25 g horizontal and .72 g vertical).

1.3 Earthquake history in other areas of the United States

Other significant earthquakes that have occurred in recent history near Navy graving docks and ship lift systems are as follows:

On April 13th 1949 a magnitude 7.0 earthquake occurred in Olympia, Washington about 36 miles south of the now Puget Sound Naval Shipyard (Bremerton) [1]. On April 29th 1965 a magnitude 6.5 earthquake occurred near Seattle, Washington about 18 miles from Bremerton. Both caused heavy property damage over a wide area of Washington and Oregon. Buildings which apparently had been damaged in 1949 incurred additional damage in 1965 [1].

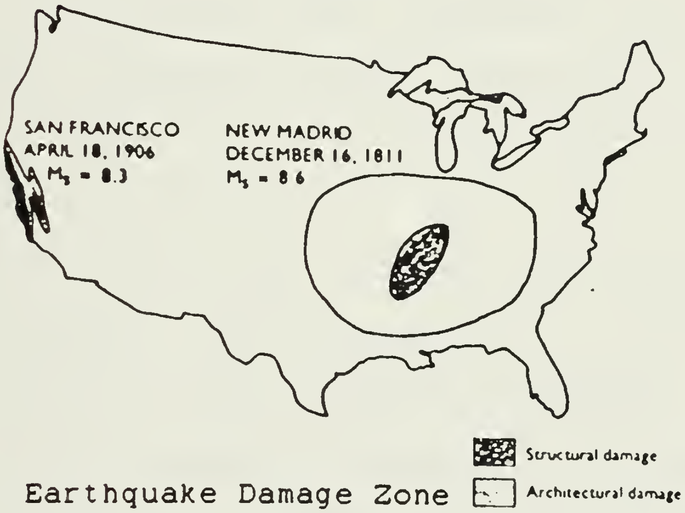
On November 29th 1975 a magnitude 7.2 earthquake occurred in Honokaa, Hawaii 184 miles from Pearl Harbor Naval Shipyard. This was the largest earthquake in Hawaii since 1868. It was felt in Oahu where the shipyard is located.

Franklin Falls Dam, New Hampshire, 55 miles west of Portsmouth Naval Shipyard, experienced a 4.5 magnitude earthquake January 19th 1982. The maximum horizontal acceleration recorded was .52 g's [11].

New England experiences three to five earthquakes every year [4]. The last major earthquake occurred on November 18th 1755 at Cape Ann, Massachusetts which is approximately 40 miles south of Portsmouth, New Hampshire. It had a magnitude of approximately 6.0 on the Richter scale. The shock was felt from Chesapeake Bay to Nova Scotia. In Boston, walls and chimneys were thrown down. Waves like the swelling of the ocean were reported on the surface of the earth. Many people on vessels felt shocks like the ships were striking bottom [1]. The amount of earthquakes that New England experiences in 150 years California experiences in 1 year. Although east coast earthquakes are more infrequent, due to the more homogeneous geological conditions, earthquakes are more widely felt when one occurs.

A major earthquake occurred August 31st 1886 fifteen miles northeast of Charleston, South Carolina. A series of severe shocks left more than 60 dead and many more injured. There was serious property damage. Much of Charleston was built on land fill which contributed to the damage. Earth waves similar to ocean ground swells were seen. They were estimated to be two feet high in certain places. There were severe flexures of railroad track. The area of severe effect was large. Within an area of 100 miles the destruction would have been severe but settlements were few and far between [1].

Between December 1811 and February 1812, three extremely large earthquakes (greater than 8.0 in magnitude) devastated New Madrid, Missouri which is 380 miles north of where Ingalls Shipbuilding is located today. These earthquakes, the largest of which was magnitude 8.6, are among the greatest earthquakes in known history. Topographic changes occurred over an area of 30,000 to 50,000 square miles. The total area shaken was over 2,000,000 square miles as shown in figure (1.4).



1811 Earthquake Damage Zone

Figure 1.4

The direction of the Mississippi River was changed for a period of time due to this earthquake. For several days following the final earthquake the earth was in constant tremor. After shocks lasted for two years. The shock was felt from Canada to New Orleans, Louisiana and as far east as

Boston, Massachusetts 1100 miles away. The shock was felt distinctly in Washington D.C. and people were badly frightened. Fissures were created that were up to 500 feet long and 20 feet deep.

1.4 The Earthquake Challenge

As has been shown, earthquakes can occur virtually any where in the United States where submarines can be drydocked. They can produce tremendous forces and ground displacements which seriously threaten the safety of drydocked submarines.

Earthquakes usually occur without any warning. They reach maximum strength within seconds. It is impossible to take precautions such as an emergency undocking. Presently there is no reliable means of predicting the occurrence of earthquakes. Therefore, if submarines are to continue to be drydocked in earthquake high risk areas the drydock blocking systems must be designed to resist expected earthquake excitation [12].

CHAPTER 2

SUBMARINE DRYDOCK BLOCKING SYSTEM ANALYSIS HISTORY

2.0 Background

The major objective in the design of the docking block arrangements for Navy ships is to provide blocking systems which are adequate to support the ship's weight and to survive earthquake motions up to an intensity which will destroy the dock itself. Presently, these design methods involve approximating the seismic response by using a specified horizontal acceleration, the magnitude of the peak acceleration being 0.2 g. The potential for overturning, sliding, or crushing of the blocking system is then assessed on an "equivalent static" basis with a horizontal force applied at the ship's center of gravity.

A more rigorous examination of the seismic response of submarines was undertaken by B. V. Viscomi (1981) [13] using a dynamic equation of motion. This analysis involved determining peak ground accelerations which would cause the submarine to lift off one set of side blocks for a variety of blocking arrangements. The submarine was considered to be a rigid body with a single (rotational) degree of freedom. The docking blocks were thus necessarily assumed to be stable and to respond elastically to load.

Using the quasi-static method it was found that present drydock blocking systems could survive an earthquake of the magnitude of the 1940 El Centro earthquake (0.45 g peak acceleration). However, studies conducted at MIT under the direction of Professor Karr analyzing the problem using one degree of freedom (Karr,1985) [14], two degree of freedom (Barker,1985) [15], and three degree of freedom (Sigman,1986) [16] models indicated that failure would occur at substantially lower earthquake magnitudes.

This significant discrepancy warranted further examination and verification. Each of the governing differential equations of motion used for the one, two, and three degree of freedom models were rederived and confirmed correct. More precise drydock block stiffnesses were calculated using accurate block dimensions and block numbers obtained from the submarine docking plans. This block information was then input into drydock block stiffness calculation spreadsheets (Hepburn & Luchs,1986) [17].

It was verified that the computer code correctly calculated the solutions to the equations of motion. Specifically, in the three degree of freedom case, the Fourth Order Runge-Kutta method used for solving the non-linear, coupled, system of second order differential equations was found to be correct. All eleven submarine drydock block

systems studied, including four submarine classes (SSBN 616, SSBN 726, SSN 688, and SSN 637), were then analyzed using the updated programs and data files.

The results from the one, two, and three degree of freedom computer runs indicated that the eleven submarine systems could withstand approximately 13 to 25 percent of the El Centro Earthquake ground motion amplitudes. This range is slightly lower than that determined by Sigman and is a worse condition. The one, two, and three degree of freedom models gave very similar results which helped to verify the validity of each method, especially since the one and three degree of freedom methods were based on a totally different method of solution. However, a two or three of degree of freedom method is required to determine the exact blocking system failure modes. The four modes of failure of the blocking system addressed were:

(1) Crushing of the keel and bilge blocks.

(2) Sliding of the block interfaces.

(3) Overturning of the blocks.

(4) Lifting off of the ship from port or starboard side blocks or keel blocks.

For all the blocking systems, the dynamic analysis indicated failure at lower earthquake magnitudes then would be indicated by the quasi-static approximations. Detailed descriptions of the analysis and findings of one, two, and three degree of freedom response of submarines are discussed in the "Docking Under Seismic Loads Final Report" (Karr,1987) [18].

2.1 Thesis Outline

The purpose of this thesis is to investigate the effects of incorporating the non-linear properties of existing and potential blocking materials into the three degree of freedom model. This study includes the procedures used in determining blocking material stiffness, damping, and frictional characteristics.

Chapter 3 summarizes the results of previous research using linear blocking materials. The computer program used in this research to determine system response is described. Chapter 4 investigates existing and potential blocking material non-linear characteristics such as stress-strain behavior, damping, and anisotropic properties. In addition, chapter 4, describes how the stiffnesses were determined for multi-layered blocking piers.

Chapter 5 examines the properties of the wood material currently being used in blocking systems. Specific characteristics of Douglas fir and oak are discussed. Results of drydock block compressive tests are used to model wood as a bilinear stiffness material. A computer program subroutine is developed to include this bilinear characteristic of the wood in the main three degree of freedom model.

Rubber is evaluated in chapter 6 as a potential blocking material. Compressive test data is also used to model rubber as a different type of bilinear stiffness material. Another computer program subroutine is developed to include this behavior in the main program.

Chapter 7 describes the use of dynamic isolators in the blocking system. The isolators' horizontal bilinear behavior is incorporated into the main three degree of freedom program using the same bilinear subroutine used for wood. The isolators' physical characteristics and previous applications are described.

The original eleven systems evaluated in previous research are reexamined in chapter 8 taking into account the non-linear properties of the wood and rubber actually used in these systems. Chapter 8 then compares the results of the non-linear material analysis to previous linear material models. In chapter 9, conclusions are drawn and recommendations are made for further study in this area.

2.2 Description of the Three Degree of Freedom System and Equations of Motion

The three degree of freedom model of the submarine drydock blocking system at rest as developed by Sigman (1986) [16] is shown in figure (2.1). This is the system used as a baseline for this thesis. This figure is a two dimensional representation of the submarine and dry dock with the keel and side block piers modeled as horizontal and vertical springs and dashpots.

The point CG1, figure (2.1) is the initial location of the center of gravity of the submarine. The point K is the initial location of the keel of the submarine. The point K', insert figure (2.2), is the location of the keel after horizontal and vertical translation has occurred, rotation occurs about this point. KG is the distance from the keel to the center of gravity. The distance br is the transverse distance between the center of the caps of the port and

starboard side blocks. The horizontal and vertical spring constants are as designated in the figure.

The system is excited by horizontal and vertical drydock accelerations $\ddot{x}_g$ and $\ddot{y}_g$ respectively. The entire dry dock and submarine system moves relative to a fixed reference frame. The excited system is shown in figure (2.2). The system of equations are expressed in terms of motion of the submarine relative to the dry dock. Motion in the longitudinal, z direction, is ignored.

The point CG2, figure (2.2), is the location of the center of gravity of the submarine relative to the fixed reference frame after horizontal displacement u and vertical displacement v. The point CG3 is the location of the submarine's center of gravity after the additional absolute rotation theta, θ. The insert at the bottom of figure (2.2) is a close up of the keel area of the submarine during this motion. The displacements illustrated are described as follows:

The relative horizontal displacement coordinate x is the displacement of the submarine keel with respect to the dry dock. The displacement u is the position of the keel relative to the fixed reference frame. With ground motion x_g the following equations hold:

$$x = u - x_g$$

$$u = x + x_g$$

$$\ddot{u} = \ddot{x} + \ddot{x}_g \qquad (2.1)$$

Similarly for vertical translation the following equations hold:

$$y = v - y_g$$

$$v = y + y_g$$

$$\ddot{v} = \ddot{y} + \ddot{y}_g \qquad (2.2)$$

The coupled non-linear three degree of freedom equations describing the system motion as developed by Sigman are as follows:

$$M\ddot{x} + M\overline{KG}\ddot{\theta} + C_h\dot{x} + C_{h\theta}\dot{\theta} + (2khs+khk)x = -M\ddot{x}_g \qquad (2.3)$$

$$M\ddot{y} + C_v\dot{y} + (2kvs+kvk)y = -M\ddot{y}_g \qquad (2.4)$$

$$I_p\ddot{\theta} + M\overline{KG}\ddot{x} - M\overline{KG}\ddot{y}\theta + C_\theta\dot{\theta} + C_{\theta h}\dot{x} + [(br^2/2)kvs$$
$$-WKG]\theta = -M\overline{KG}\ddot{x}_g \qquad (2.5)$$

Three Degree of Freedom Submarine
Drydock Blocking System Model at Rest

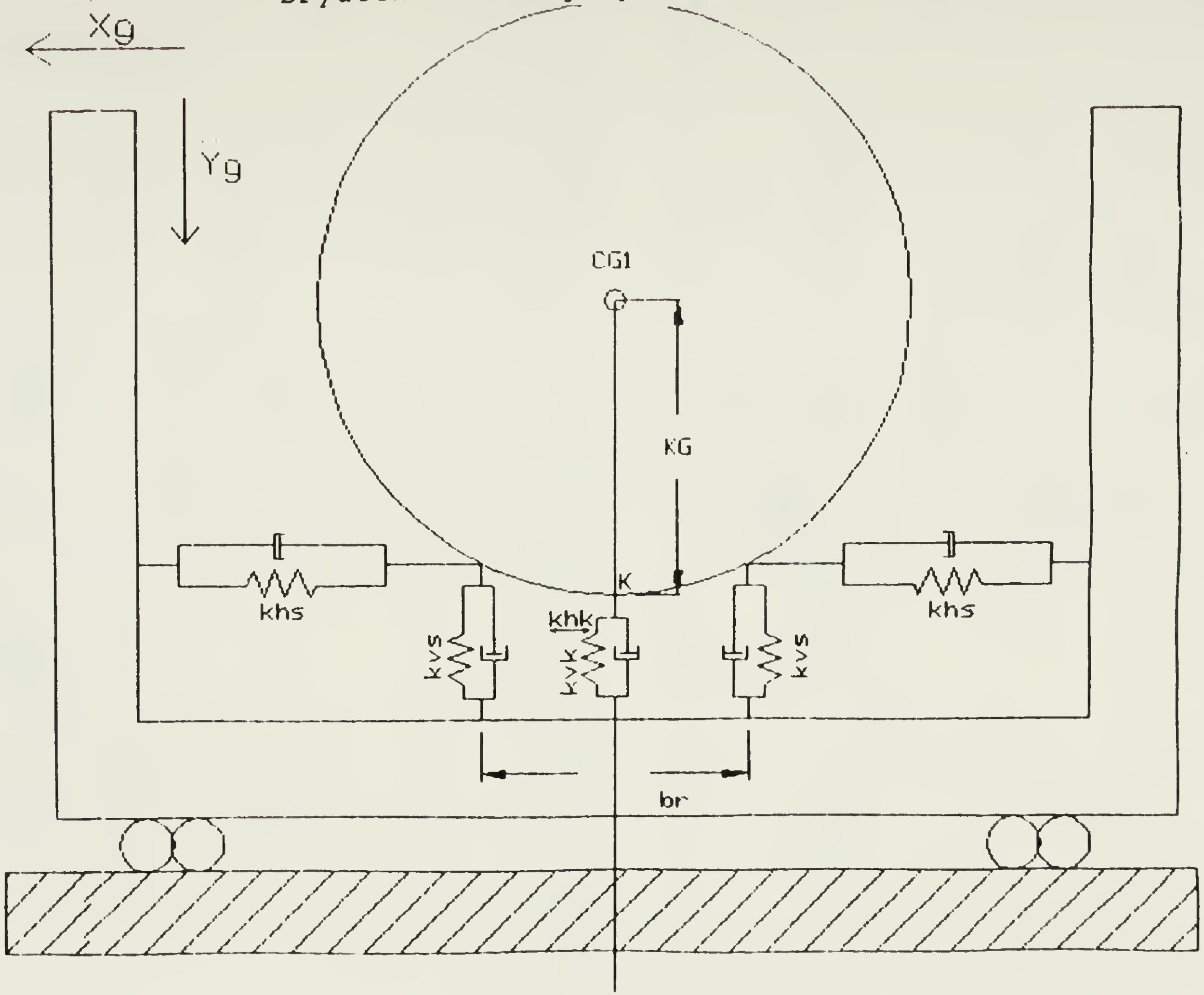


FIGURE 2.1

Three Degree of Freedom Submarine Drydock Blocking System Model Excited

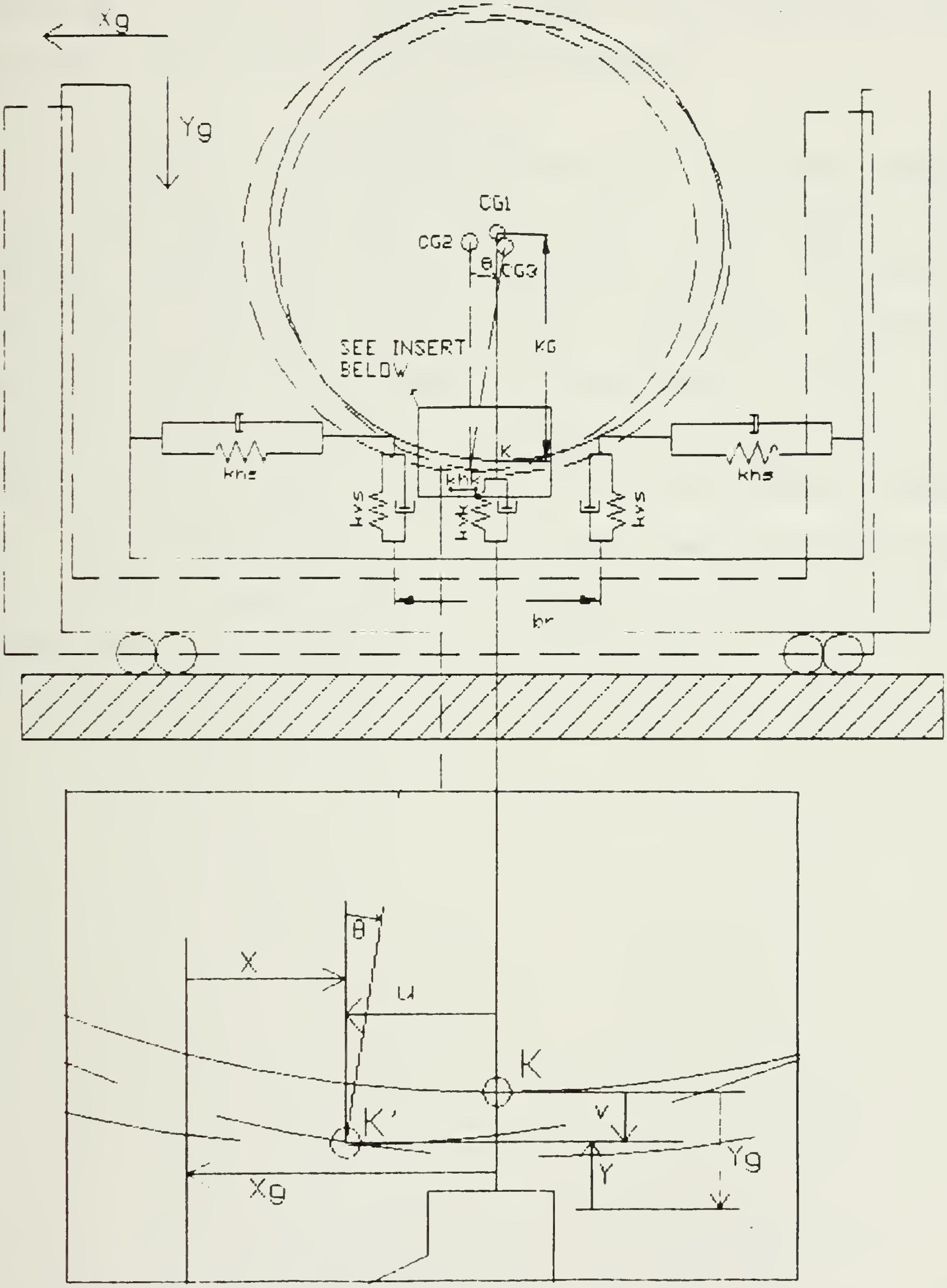


FIGURE 2.2

In equations 2.3 through 2.5, M is the mass of the submarine, Ik is the rotational moment of the submarine about the keel, and W is the weight of the submarine.

In order to solve these differential equations Sigman (1986) [16] used the fourth order Runge Kutta method and computed the solutions using a Fortran program. The damping coefficients were calculated in the program using the modal analysis method. The program includes several flags which identify various failures of the submarine drydock blocking system and are listed in section 2.0. This computer program with the failure modes is utilized as a baseline program for this thesis. The program is modified to include material properties. These changes are discussed later.

CHAPTER 3

SUMMARY OF PREVIOUS RESEARCH USING LINEAR MATERIALS AND SIMPLE GEOMETRY

3.0 Description of Systems Analyzed

The eleven typical submarine drydock blocking systems used by Sigman (1986) [16] are the baseline systems for this thesis. The submarine drydock blocking parameters corresponding to each system and the appropriate Naval Sea Systems Command (NAVSEA) docking drawings are shown in Table 3.1.

TABLE 3.1

SUBMARINE DRYDOCK BLOCKING SYSTEMS

SYSTEM #	HULL #	BLOCK TYPE	LONGITUDINAL SPACING	NAVSEA DRAWING #
1	616	COMPOSITE	8 FT	8452006640
2	616	COMPOSITE	16 FT	8452006640
3	616	TIMBER	8 FT	8452006640
4	616	TIMBER	16 FT	8452006640
5	616	TIMBER SIDE COMPOSITE KEEL	16 FT	8452006640
6	726	COMPOSITE	8 FT	8454862749
7	726	COMPOSITE	12 FT	8454862749
8	726	COMPOSITE	16 FT	8454862749
9	688	COMPOSITE SIDE TIMBER KEEL	12 FT	8454403511
10	637	COMPOSITE SIDE TIMBER KEEL	12 FT	8452140554
11	637	COMPOSITE SIDE TIMBER KEEL	16 FT	8452140554

Composite is the term used to describe a "standard" Navy drydock blocking pier which consists of concrete blocks and wood layers. The concrete block dimensions are usually 42 inches wide and 48 inches long. Its height can range from 30 to 60 inches. A six inch oak cap is attached to the top and bottom of this block and is included in its dimensions. On top of the concrete block is a layer of oak with a two to four inch cap of Douglas fir. The Douglas fir is used to protect the hull from stress concentrations due to slight hull discontinuities.

A timber pier uses no concrete. Oak is used from the dock floor to the cap. A pier is the block layer arrangement required for one side block or one keel block. Keel piers are normally butted together (cribbed) along the entire length of the keel. Longitudinal spacing is the longitudinal distance between the side block caps along the hull.

3.1 Assumptions Used in Barker's and Sigman's Analyses

Barker (1985) [15] and Sigman (1986) [16] assumed that all of the blocking materials were linear, elastic, and isotropic. Because small deformations were expected the side block and keel block heights were assumed to be the same (60 inches in all cases); therefore, horizontal and vertical blocking stiffnesses were completely uncoupled. The actual

height of the side blocks above the keel baseline was also not taken into account when calculating sliding forces.

The submarine was assumed to be a rigid body. The mass of the blocks was neglected. Five percent critical damping was used throughout. The model was assumed to be valid as long as the drydock blocks remained rigidly attached to the dock floor, the blocks did not slide, and the submarine remained in contact with all the blocks. Whenever any of these conditions broke down the computer program flagged the condition as a failure.

3.2 Results of Sigman's Analysis

All of Sigman's [16] results were based on an excitation by the 1940 (0.45 g) El Centro earthquake acceleration time history. These accelerations were applied at the base of the dry dock, and coupling of the ground and dock floor was ignored. The El Centro earthquake records are used throughout the civil engineering community as a standard for structural design. Figure (3.1) is a plot of the first twenty seconds of the acceleration time history used by Sigman in his analysis.

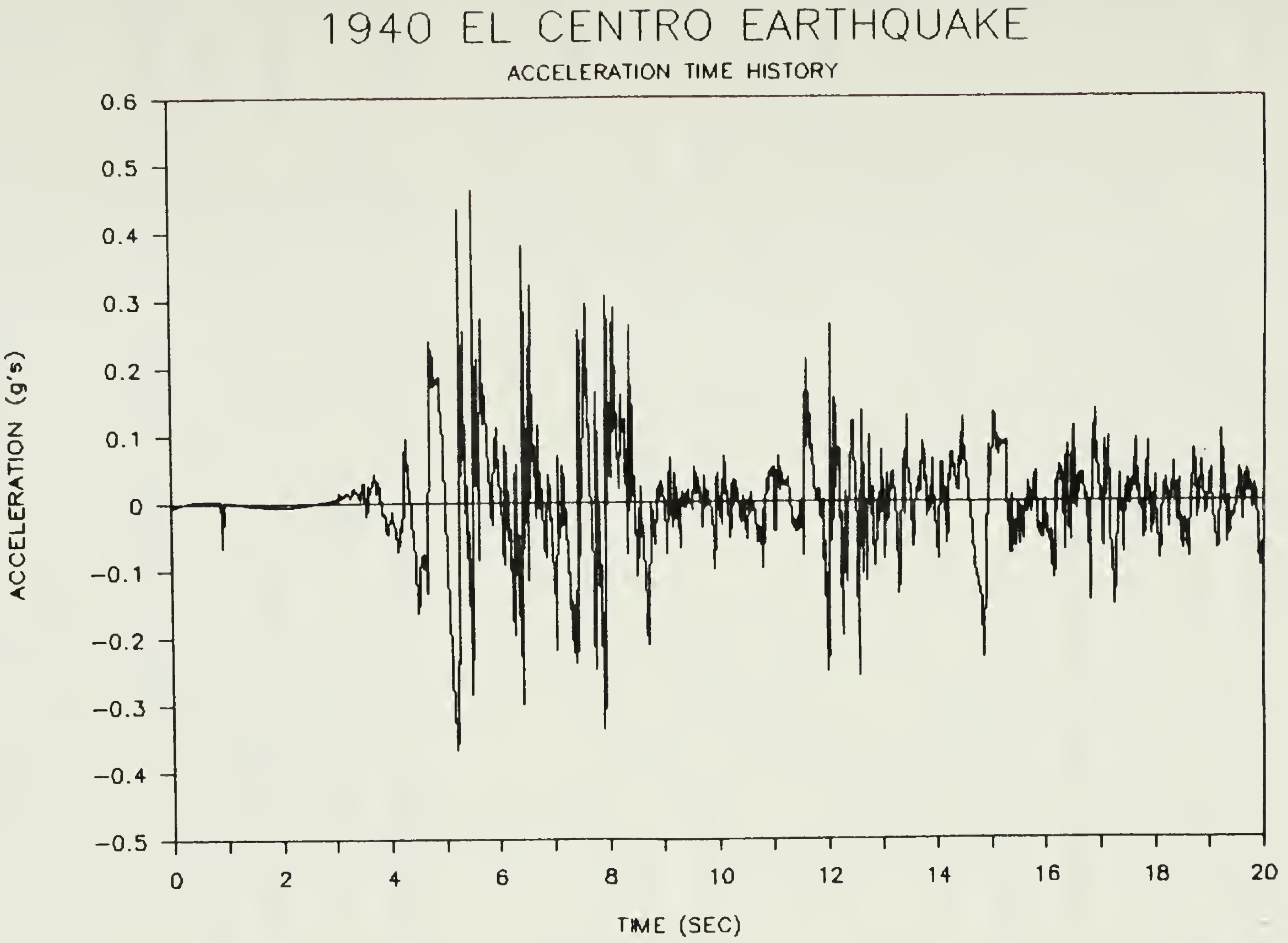

1940 EL CENTRO EARTHQUAKE
ACCELERATION TIME HISTORY
ACCELERATION (g's)
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
−0.4
−0.5
0
2
4
6
8
10
12
14
16
18
20
TIME (SEC)

FIGURE 3.1

Upon analyzing the submarine drydock blocking systems, Sigman found that all eleven systems failed well below the 0.2 g peak acceleration requirement as set forth in NAVSEA Technical Manual 997 [19]. All eleven systems failed by side block liftoff. Survival ranged from 0.06 to 0.18 g's, as determined by the computer program described section 3.3. The graving docks at Long Naval Shipyard and Mare Island Naval Shipyard are designed to withstand a peak of acceleration of 0.26 g's before construction joint failure occurs [20]. Sigman's analysis shows that current submarine drydock blocking systems will fail well prior to the dry dock itself. His analysis also showed that the quasi static method currently used by the U.S. Navy for seismic response analysis seriously underestimates the forces the systems will experience. This unsatisfactory condition is the motivation for the research conducted in this thesis.

Figure (3.2) illustrates the survival percentage of the eleven submarine systems subject to the 1940 El Centro Earthquake. Included in this figure is the line above which dry dock failure would occur. This clearly illustrates that inadequacy of current blocking system design.

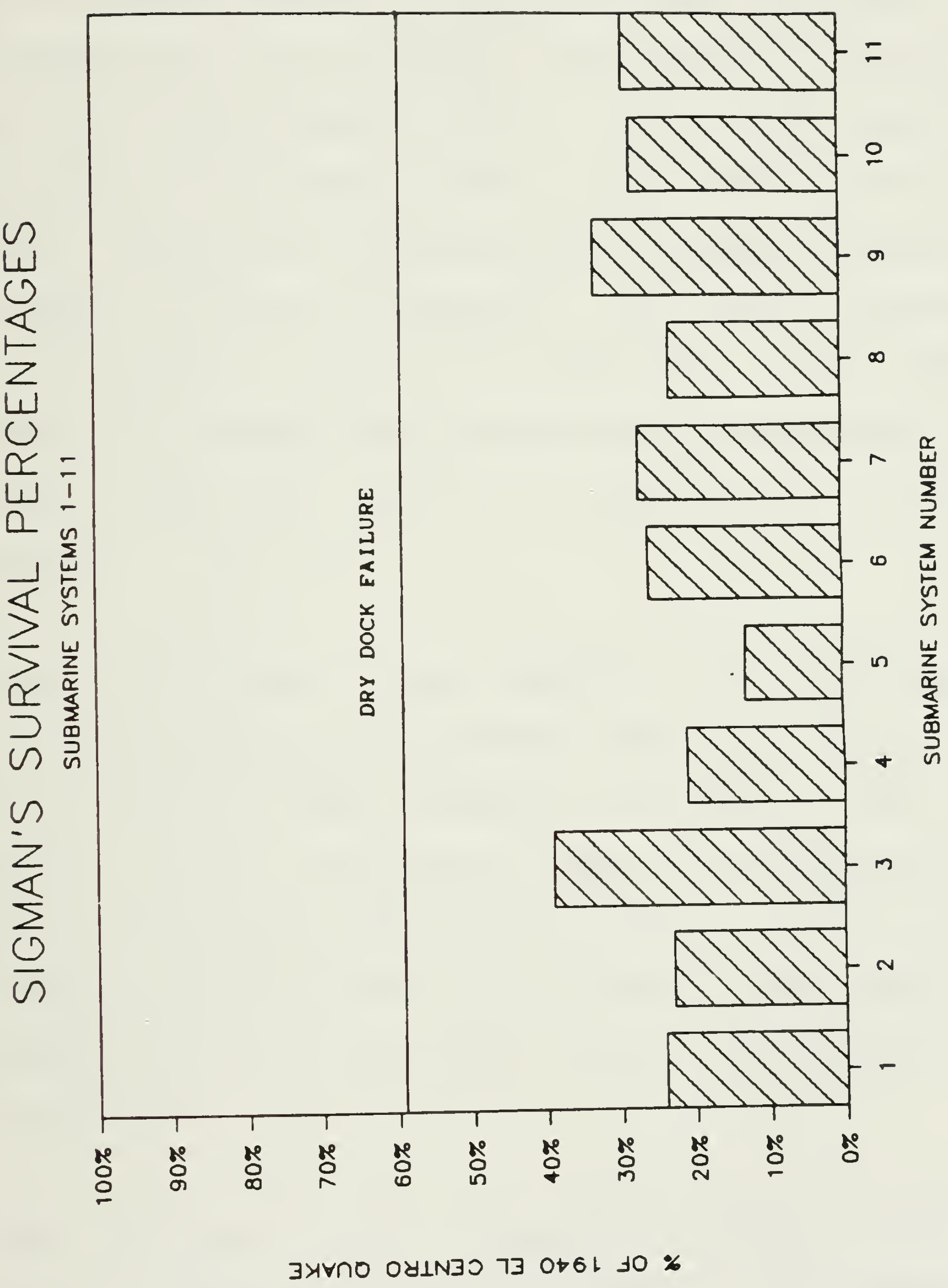

SIGMAN'S SURVIVAL PERCENTAGES
SUBMARINE SYSTEMS 1–11
DRY DOCK FAILURE
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% OF 1940 EL CENTRO QUAKE
1
2
3
4
5
6
7
8
9
10
11
SUBMARINE SYSTEM NUMBER

FIGURE 3.2

3.3 Description of the Computer Program Used in This Thesis

The computer program used to analyze the submarine drydock blocking systems in this thesis was developed jointly with Luchs [21] and is based on the program developed by Barker [15] and Sigman [16]. The most significant modifications with respect to this thesis made to this program included the addition of subroutines to incorporate non-linear stiffnesses of blocking materials. Two specific subroutines were developed to model the materials. They were the "BILINALL" and "RUBBER" subroutines which are described later. The main program and subroutine listings are included in Appendix 1.

The main program called "3DOFRUB" first reads submarine drydock blocking system parameters from a data file. It then calculates system's modal masses, stiffnesses, and natural frequencies. Modal analysis is used to determine damping coefficients using the specified percent critical damping. The horizontal acceleration time history (and vertical if applicable) are input from data files. Variables and flags are initialized.

The main loop of the program then begins. This loop impliments the Runge-Kutta equations. The appropriate blocking material stiffnesses are recalculated each time step. Based on the blocking material input data the appropriate

subroutines are used by the program to calculate their stiffnesses.

Each time step, keel and side block forces are calculated. Then the system is tested for failure and the appropriate failure modes are flagged. The program begins by using 100 percent of the input acceleration time history. If failures occur, it carries out repeated loops through the whole history each time decreasing the input acceleration. This continues until the system survives a complete loop through the time history. In order to speed up the processing, the acceleration time history are limited to 2000 inputs which, for most records, means twenty seconds of the earthquake. For most earthquakes this captures the worst portion of the excitation and is considered adequate for design purposes. Finally, the program output includes displacements, failure modes, and times of failures for each percent of the earthquake acceleration tried. In addition, force and displacement data files are created as chosen by the user for use in plotting system response. A sample input data file and output file are also included in Appendix 1.

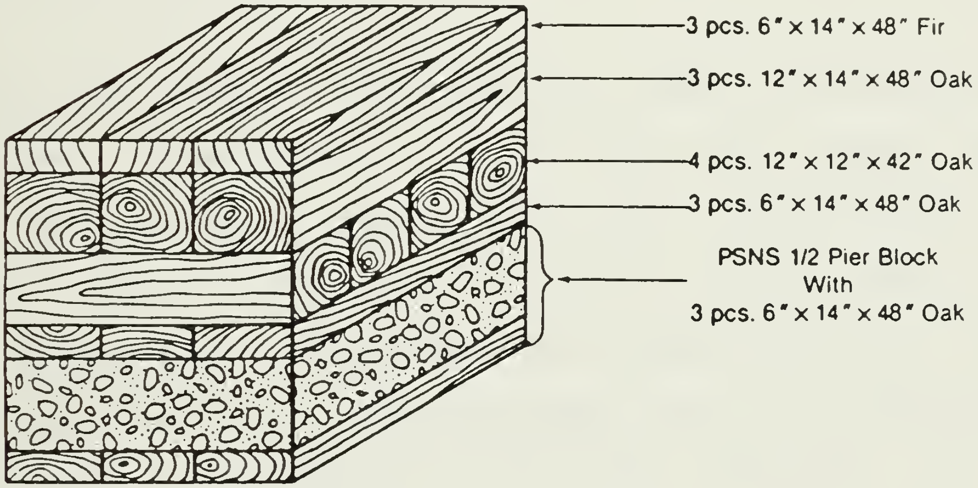
CHAPTER 4

EXISTING AND POTENTIAL BLOCKING MATERIAL CHARACTERISTICS AND PROPERTIES

4.0 Existing Blocking Materials

Virtually all U.S. Naval shipyards and private yards which dock U. S. Navy ships use soft and hard woods as drydock blocking materials. Concrete is used in the base of most of the blocking piers; however, the wood products comprise the upper portion of the blocking system which is in contact with the ship. A drawing of a typical Navy composite keel block is illustrated in figure (4.1) [22]. The soft wood is used in a "soft cap" (2 to 6 inches) on top of the hardwood to protect the hull from stress concentrations.

Previous analyses assumed that all the blocking materials were linear, elastic, and isotropic. While these are reasonable assumptions for concrete, that is not the case for wood. Typically the soft wood used in drydock blocking systems is Douglas fir or woods of similar properties. The hard wood used is usually white oak or similar hard woods. The capping and hard wood materials that shipyards receive from their suppliers have highly variable properties.


3 pcs. 6" x 14" x 48" Fir
3 pcs. 12" x 14" x 48" Oak
4 pcs. 12" x 12" x 42" Oak
3 pcs. 6" x 14" x 48" Oak
PSNS 1/2 Pier Block
With
3 pcs. 6" x 14" x 48" Oak

57" BUILD-UP

Typical Navy Composite Keel Block

FIGURE 4.1

4.1 General Wood Properties

4.1.1 Variation in Wood Types

When a drydock blocking system is constructed by a shipyard, either new wood just obtained or old wood on hand is used. This applies to the soft cap and hard wood portions of the system. Sometimes new wood is combined with old wood in random ways in the same blocking pier.

The wood received from suppliers comes from various cuts from trees. Sometimes the cuts include the "boxed heart" (center pith material) of the wood where properties of the wood vary widely. Sometimes the grain of the wood in the timber is primarily horizontal or vertical depending on the location of the cut. The wood used comes from various parts of the country; therefore, the moisture contents and ring sizes and thus strength properties of the wood vary dramatically. Therefore, blocking piers in use today for drydocked submarines contain materials which have uncertain characteristics.

Panshin [23] found that for temperate zone woods, the portion of the timber formed in the early part of the growing season has larger cells and relatively lower density than that formed in the later season. This part is called the early wood and the denser and usually darker wood formed in the last

part of the growing season is called late wood. The transition between the early and late wood may be gradual or abrupt giving rise to differentiations between certain hard woods and between ring-porous and diffuse-porous hardwoods.

Panshin also states that wood produced by trees of the same species is often mistakenly assumed to be identical in all structural and physical characteristics. In fact, different specimens of wood even from the same tree are never identical and are similar only within broad limits.

4.1.2 Anisotropic Properties of Wood

A material which has physical properties which depend upon direction is said to be anisotropic. The cell wall in wood exhibits definite anisotropy because of the structural organization of the materials composing it. According to Panshin (1980) [23], the nature of the thin walled tubular cells in wood and their arrangement with respect to the axis in the stem contributes to this nonuniformity. As a consequence, compressive, tensile, and shear strengths vary widely between the longitudinal and lateral directions of wood.

Bach (1968) [24] describes non-linear wood properties as follows:

> "The structural anisotropy of wood is a recognized factor that determines its elastic stress-strain relations. Wood cut from near the bark of mature trees has approximately orthotropic symmetry which requires nine elastic constants (3 Young's moduli, 3 shear moduli, and 3 Poisson's ratios) to define its response to generalized stress. In turn, the nine elastic constants for a given wood specimen are functions of time, moisture content, temperature, and stress history."

For this thesis wood is assumed to be an orthotropic material having different properties in each of three principle directions. These three directions are shown in figure (4.2) [25] below.

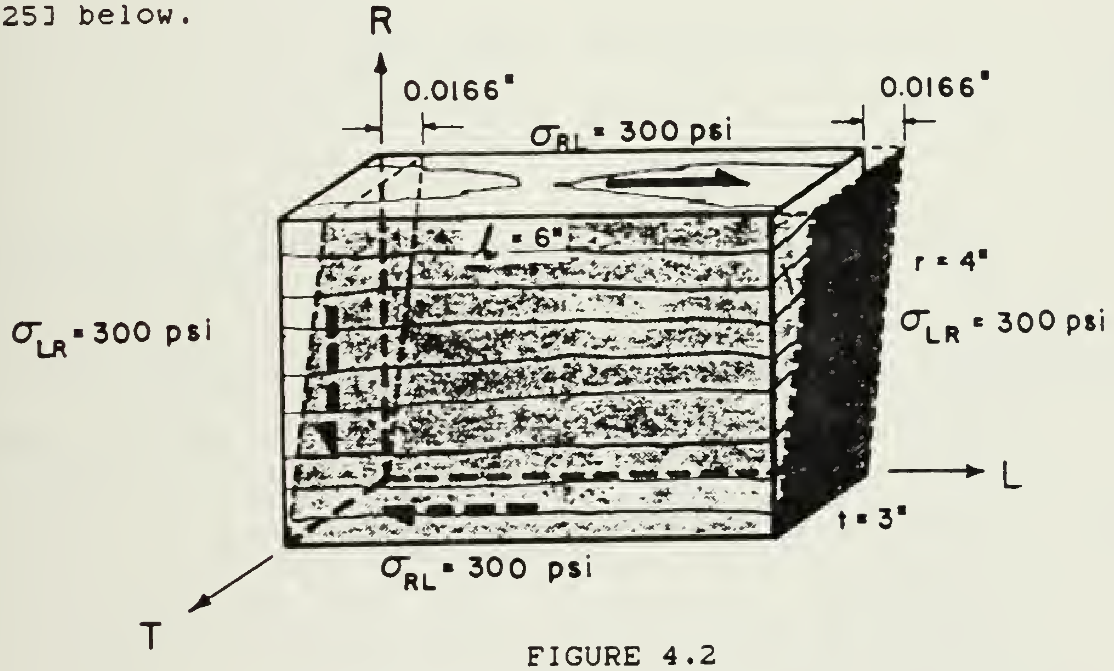


FIGURE 4.2

Distortion of a wood block caused by shear stress σ_{RL} (σ_{LR}).

The three principle directions shown in figure (4.2) are tangential, T, longitudinal, L, and radial, R. The modulus of elasticity of wood perpendicular (tangential) to the grain is designated as E_T. The modulus of elasticity in the longitudinal direction is E_L, and the modulus of elasticity in

the radial direction is E_R. G_{LR} is the modulus of elasticity, also called the modulus of rigidity, due to shear, τ_{LR} in the plane LR as shown in figure (4.2).

Bodig (1983) [25] states that the ratios of the three moduli of elasticity for wood vary with species, moisture content, temperature, rate of loading, and a number of other variables. In spite of the many sources of variation, in general the moduli are approximately related according to Bodig by the following ratios:

$$E_L : E_R : E_T \qquad 20 : 1.6 : 1 \tag{4.1}$$

$$E_L : G_{LR} \qquad 14 : 1 \tag{4.2}$$

The *Wood Handbook*'s [26] number for $E_L/G_{LR} = 13.68$.

A simple relationship for shear strain of wood subject to shear stress, τ_{LR}, is described by Bodig as follows:

$$\gamma_{LR} = \tau_{LR}/G_{LR} \tag{4.3}$$

4.1.3 Strength Variations in Wood

Panshin (1980) [23] states that wood is 4 to 12 times stronger in compression parallel to the grain than it is perpendicular to the grain. Figure (4.3) [23] is a graphic representation of the actual variation for compression

strengths as the angle between grain orientation and direction of load application varies (1) from parallel to perpendicular to the grain and (2) between the radial and tangential directions with respect to the growth rings. This figure is for a species of Scotch pine.

Most wood products literature lists compressive strengths and moduli in the parallel direction for major wood species. The compressive strength is a measure of the ability of a piece to withstand loads in compression parallel to the grain up to the point of failure. Because of the submarine drydock blocking systems' geometry, loads vary from perpendicular to parallel; therefore, the wood blocking material strengths and moduli were varied appropriately using figure (4.3).

Specific gravity of wood, according to Panshin [23], because it is a measure of the relative amount of solid cell wall material is the best index for predicting strength properties of wood. He also mentions that the specific gravity of wood depends upon: (1) the size of the cells, (2) thickness of the cell walls, (3) the interrelationship between the number of cells of various kinds in terms of (1) and (2).

Compressive Strength of Wood at Various Grain Angles

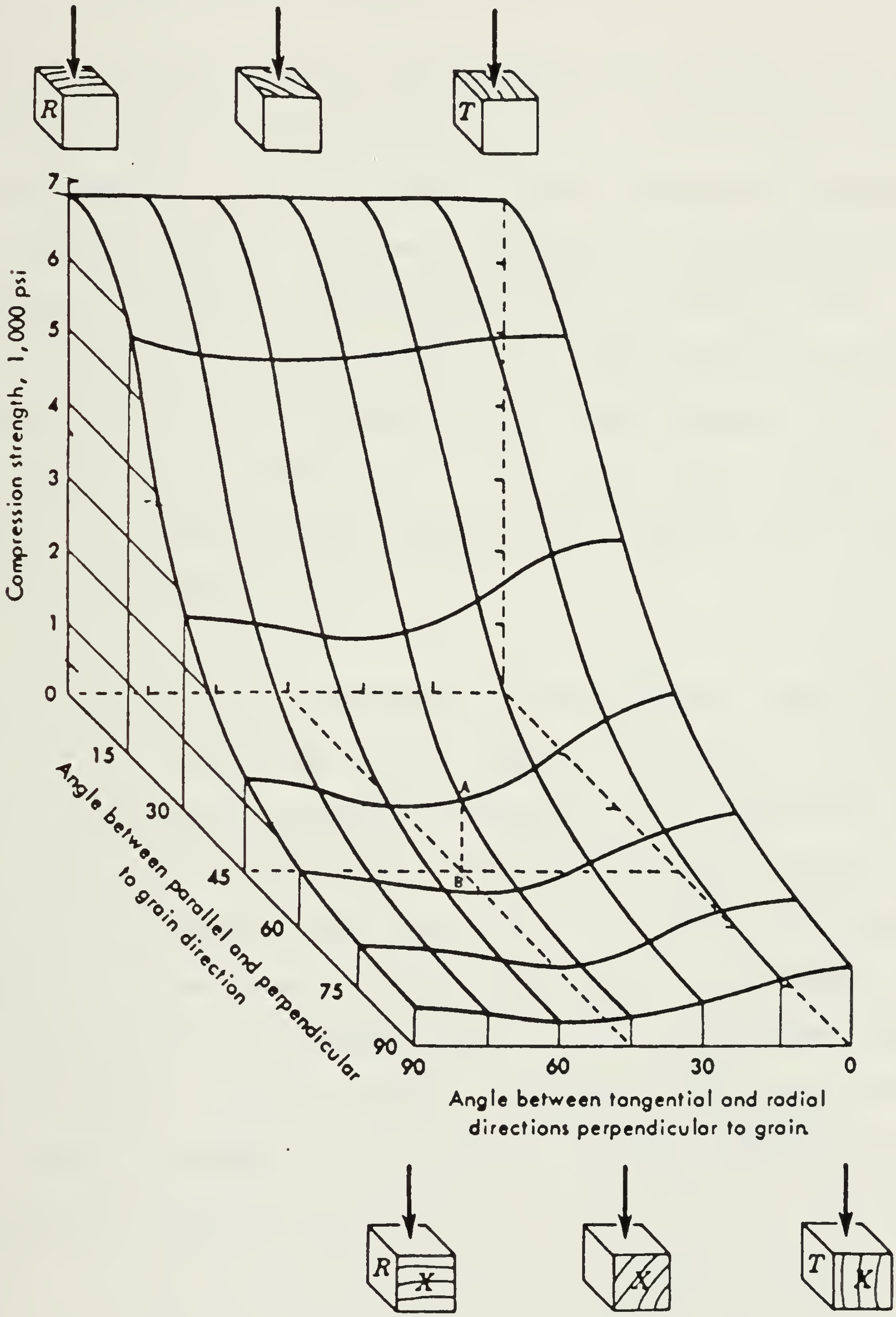


FIGURE 4.3

4.1.4 Non-linear Properties of Wood

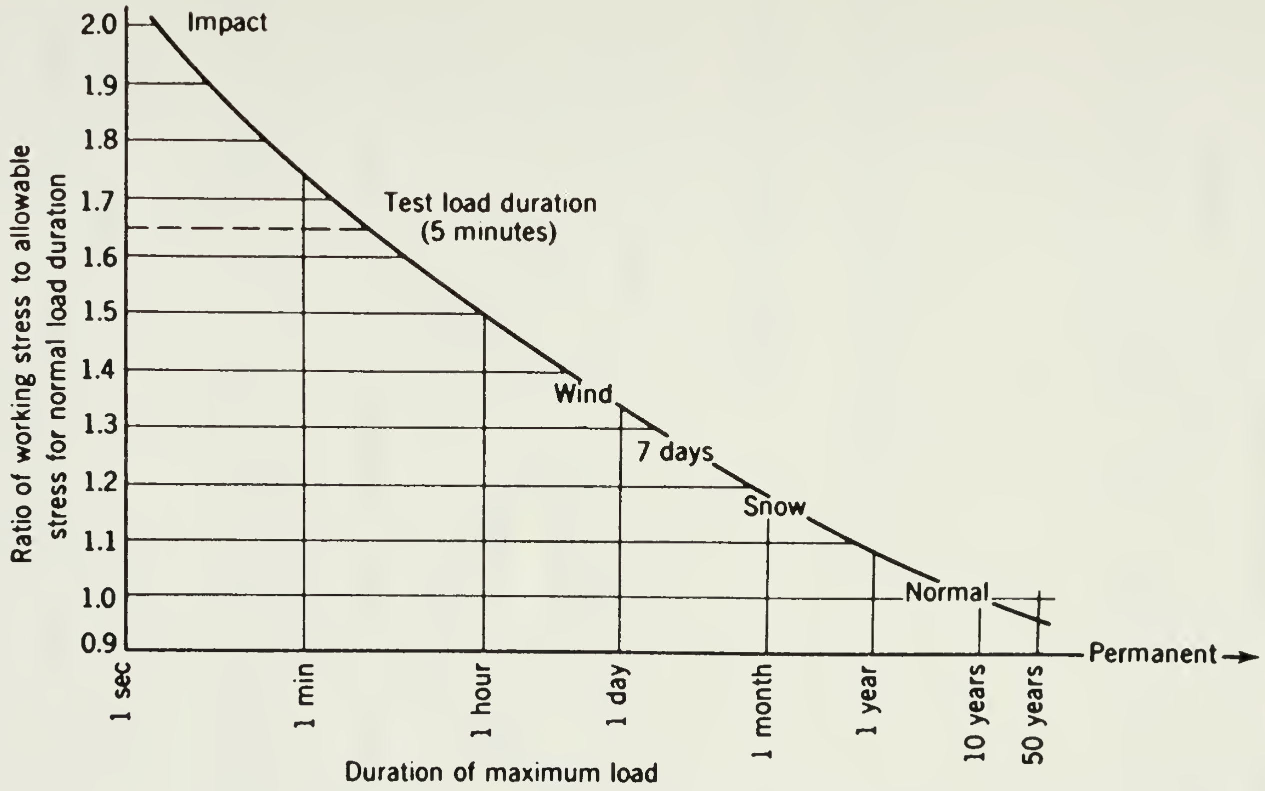
For any given piece of wood subject to stress, the load deformation curve reaches a proportional limit, beyond which the total deformation is non-recoverable and some permanent set is imposed on the specimen. Permanent displacement on a stress/strain curve, an indication that the strain did not return to zero when the applied load was removed is called "permanent set". The stress/strain relationship is also highly dependent on the rate at which the load is applied. Increasing the rate of load application results in higher strength values [25].

The steepness of the slope of the elastic line is a measure of the magnitude of the elastic modulus. In some kinds of wood there is almost no demarcation of the end of the elastic portion of the curve. The proportional limit can scarcely be defined. The set is attributed to plastic deformation of the wood. This deformation increases with applied load above the proportional limit until the piece breaks or fails in some manner. The area under the stress-strain curve represents the amount of energy absorbed by the wood during its deformation.

4.1.5 Wood Loading Rate Effects

During an earthquake the blocking material is loaded at a rate ranging between 0.5 to 20 cycles per second. Repeated removal and the application of load at a frequency that is much smaller than the natural frequency of the body is defined as "cyclic loading". According to Bodig (1983) [25] a higher rate of loading will produce higher stiffnesses, approaching the true time independent value more closely as the rate increases.

The Timber Construction Manual (1985) [27] included information on wood using tabulated design values for normal duration of loading. Normal load duration anticipates fully stressing a member to the full design value by the application of the full design load for a duration of approximately 10 years. For other durations of load, either continuously or intermittently applied, the appropriate factor determined from figure (4.4) [27] should be applied to adjust the tabulated design values. This manual states that the duration of load modifications are not applicable to the modulus. Bryant (1987) [28] confirmed that this strength/loading rate relationship applies to timbers in drydock blocking systems. Therefore, even though the modulus for Douglas fir remains the same during earthquake loading, the load at which this cap material reaches its proportional limit is increased.



Duration of load factors, derived from Forest Products Laboratory Report No. R 1916.

Effect of Load Duration on Wood Strength

FIGURE 4.4

Since earthquake durations are usually less than one minute, creep is not considered a factor during the earthquake. Kellogg (1960) [29] found that although it is known that repeated loading in tension parallel to the grain does in time reduce the ultimate strength of wood, it was found that in general 100 cycles of stress of short duration are not sufficient to incur any appreciable decrease in strength.

4.2 NAVSEA Blocking Material Study

4.2.1 Description of Tests

The large differences in the properties of wood and the increase in the loading of blocks due to heavier ships prompted the Naval Sea Systems Command to fund a blocking material study at the University of Washington [22]. Recent design changes resulting in heavier ships with smaller bearing areas have increased loads on the docking blocks to such an extent that the possibility of failure has increased.

Tests were conducted to determine the compressive strength properties of Douglas fir and oak timbers and the effect of age, size, temperature, and grain orientation on these properties. In addition, the timbers were tested in multi-layer and species configurations in full-size and scale-

model keel blocks under lateral and axial loading, and with several combinations of wood and steel interfaces to evaluate friction and cribbing properties. The tests were conducted at the University of Washington Structural Research Laboratory between October 1984 and September 1985.

4.2.2 Strength Properties of Timbers

According to this study [22], the individual timber tests showed a wide range of strength values (FSPL's) for both Douglas fir and oak. There is also a considerable overlap in the distribution of FSPL between the two species. Old timbers tended to vary more in strength than new timbers. The study also states that blocks built up with timbers that have a wide range of strength values are themselves subject to wide variations in strength, with stronger blocks carrying a larger share of the load than the weaker blocks.

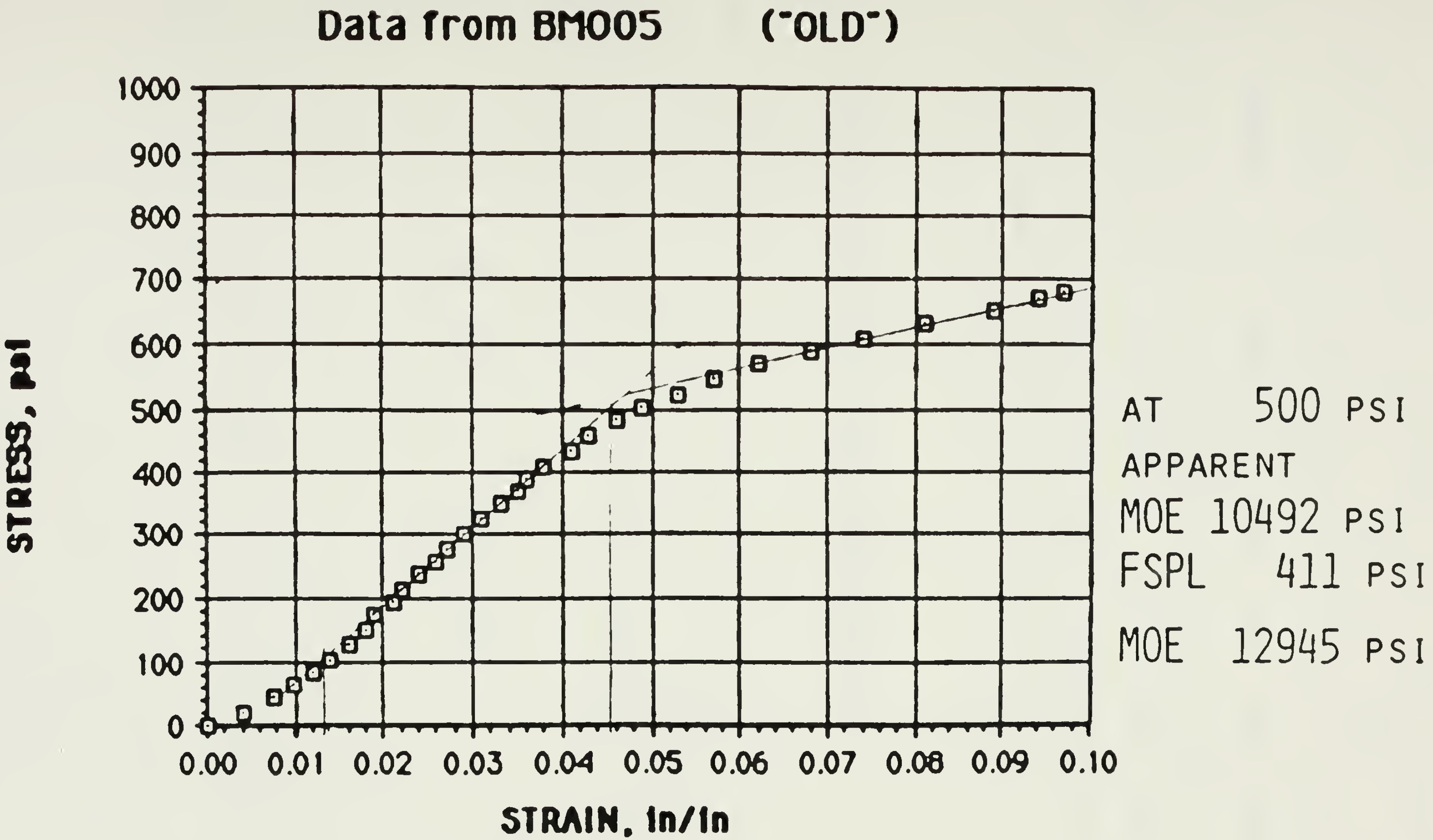
The range of strength values (FSPL's) were found to vary from 241 to 821 psi for old oak and 279 to 570 psi for Douglas fir. This shows that some timbers in service are below the desired strength. The modulus of both old and new timbers that have been compressed beyond their proportional limits are significantly lower than the average moduli of unused new timbers. As expected, compressive strengths varied less between piers than between tests on individual timbers. The

values suggest that the typical keel block in service has lost some compressive strength (FSPL) compared to new timbers and that it has lost a substantial portion of its stiffness (modulus). Test data results [22] showed that for 39 new timber samples of Douglas fir the average FSPL was 367 psi. The range was 258 to 533 psi. The standard deviation was 89 psi. The mean modulus of elasticity for this Douglas fir was 26810 psi and it varied from 11850 to 38570 psi. The standard deviation was 6160 psi.

The blocking material study found that Douglas fir capping material is subject to permanent set. During docking if the load applied to any individual timber in the block exceeds its FSPL, the timber cannot return to its original thickness even though it appears to be undamaged. Therefore, variations in the thickness of ship blocking timber should be carefully examined.

4.2.3 Stiffness Properties of Blocking Piers

The compressive stress-strain curve used in this thesis for determining the stiffness properties of the Douglas fir cap is illustrated in figure (4.5) [22]. It is based on compressive tests done on layers of old Douglas fir timbers.



Stress/Strain Curve for Old Douglas Fir Timbers

FIGURE 4.5

This figure shows the very bilinear stress-strain characteristic of Douglas fir. The two moduli used for Douglas fir were determined from this figure. In this thesis oak is assumed to remain linear and the compressive perpendicular to the grain modulus for oak (23980 psi) was obtained from the blocking material test [22] using three layers of old oak timbers . This is considered to be typical of oak used in submarine drydock blocking systems.

4.2.4 Blocking Pier Frictional Coefficients

This study also included an analysis of wood on wood and wood on steel frictional coefficients. The values for these coefficients in this thesis came from this study. They are as follows for dry conditions:

Oak/Oak	Oak/Steel
0.43	0.53

The oak on oak was used for block sliding and oak on steel was used for ship on block sliding. Fir on steel values were not available in this study.

4.2.5 Blocking Study Recommendations:

The blocking study [22] recommended that since visual identification of low strength timbers is difficult at best, a non-destructive testing system be developed to aid in identifying timber strength properties. The study strongly recommended that to increase the uniformity of drydock blocking materials laminates should be used. For example, if laminated oak timbers are judged to be suitable they would exhibit a minimum of 1/4 of the strength variation of solid timbers. They would not have the inherent defects of large sawn timbers such as grain slope, checks, shakes,and boxed hearts.

Since the study found that average strength values of Douglas Fir are not significantly less then those of oak, the use of Douglas fir as a "soft cap" does not fulfill the desired purpose. The present use of Douglas fir as a capping material results in a layer that is sometimes stronger and stiffer than the underlying oak. Because some blocks have a low modulus which allows more compression a sufficient height of wood is needed within keel blocks to allow a uniform distribution of the load and to prevent over compression. Another material is recommended which has a higher load carrying capacity than Douglas fir, but a lower modulus of elasticity. Ideally this material would return to its shape after compression and retain its load carrying capacity.

4.3 Potential Use of Rubber as Blocking Material

Rubber has properties which may make it an ideal material for use as a soft cap in a blocking pier. Rubber, commonly designated as an elastic material, is so only in the sense that it returns to its original shape after deformation. Its low modulus indicates ease of deformation under load.

Marshall (1981) [30] evaluated properties of rubber. Soft rubber, similar to natural rubber, and a hard rubber were tested in uniaxial tension and compression. Tests indicated that the rubbers were essentially isotropic in their elastic characteristics. There were no visible creep effects. Both the soft and hard rubbers exhibited linear elastic responses for strains on the order of 6 %. For hard rubber $E = 7.2$ N/mm^2 and $G = 2.44$ N/mm^2 (where E is modulus of elasticity). For soft rubber $E = 2.9$ N/mm^2 and $G = 1.01$ N/mm^2 [30].

Properties of rubber are well known and strains can be determined analytically if forces are known. Treloar (1958) [31] found that for elastomers such as rubber, theoretically predicted and experimentally determined stress-strain behavior correlated well unlike wood. An elastomer is a material which at room temperature can be stretched repeatedly to at least twice its original length. Immediately upon release of the

stress, an elastomer will return with force to its original length with no permanent set. At small strains, an elastomers stress-strain curve is approximately linear. But at larger strains an appreciable upward curvature is evident.

According to Treloar [31], the shear stress versus strain curve is approximately linear for rubber in pure shear. The modulus of rigidity corresponding to the initial portion of this curve is 4.0 kg/cm^2 (567 psi). For rubber shear stress versus shear strain is more linear than compressive stress versus compressive strain. Up to very large values of strain, shear remains very close to linear. No biaxial stress data was available for rubber; therefore, the modulus of rigidity and horizontal stiffness of rubber was assumed constant throughout this thesis. For this reason, the vertical stiffness (modulus) due to compression of the rubber was considered uncoupled from the horizontal stiffness (modulus of rigidity).

At low temperatures all rubbery polymers exhibit a sharp rise in elastic modulus and become rigid. If this material is used as a submarine blocking material, in severe cold weather the material will become much stiffer and exhibit different response to loads. According to Morton (1973) [32] coefficients of friction for rubber varied from 0.5 to 0.9. This value is significantly higher than that for wood and is another positive reason for its use as a blocking material.

Blackie (1988) [33] describes a test on natural rubber. A load deflection curve was developed for natural rubber from compressive tests done on a 2 inch thick by 7 inch wide rubber specimen vulcanized to a 3/4 inch steel plate. The length of the piece was 36 inches. From this curve a bilinear stress-strain model of natural rubber was developed. The moduli for natural rubber for this thesis were obtained from this curve.

4.4 Potential Use of Elastomeric Bearings and Damping Materials in Drydock Blocking Systems

4.4.1 General Advantages of Base Isolation of Structures

Pan (1983) [34] discusses the science behind the use of base isolation systems for reducing accelerations on structures during earthquakes. He states that base isolation is an aseismic structural design strategy in which a building is uncoupled from the damaging horizontal components of an earthquake by a mechanism that attenuates the transmission of horizontal acceleration into the structure.

An extensive series of experiments on this concept have been carried out over the last few years using the shaking table at the Earthquake Engineering Research Center, University of California Berkeley. Pan [34] reports that the results from these experiments have established the

effectiveness of this approach to aseismic design and have shown that substantial reductions in the accelerations are experienced by a building on an isolation system over one on a conventional foundation. This advantage is accompanied, however, with large relative displacements at the base level of the superstructure. The typical period of isolated structures is around 2 seconds (approximately 0.5 HZ) [34].

Kelly (1980) [35] states that a further advantage is that any inelastic action will be concentrated in devices such as energy absorbing devices that are replaceable. The ultimate in isolation, according to Kelly, would be to place the entire structure on roller bearings in which case, in principle, no horizontal force would be transmitted into the structure. However, the fact that the systems have no restoring force in the presence of wind load make the roller bearing concept impractical.

Kelly [35] further states that no base isolation system can isolate the building from all earthquake frequencies. With random input such as earthquake ground motion, there will always be some component of the input that will be in resonance with the system. The effects of this resonance can be avoided by providing a degree of damping in isolation system. Rubber bearings provide a certain amount of damping, at best equal to approximately 10 % equivalent viscous damping according to Kelly. Pan [34] also states damping in an

isolation system with elastomeric bearings can be as high as 8 to 10 %. However Kelly states that higher damping may be necessary to reduce displacements.

According to Dynamic Isolation Systems Inc., Berkeley, California, (D.I.S.) [36], seismically isolated buildings can be constructed at costs that compare favorably to the first costs of conventional fixed-based structures. Moreover, owners can reap substantial long term economic benefits in the form of reduced life cycle costs. Following an earthquake, the enhanced protection of building contents inherent in an isolated building will result in significantly reduced repair and replacement costs. The force transmitted to the building is reduced by a factor of five to ten. Instead of amplifying base accelerations, the building moves as a rigid box with uniform motion and little interstory drift.

Mayes (1984) [37] describes the design of the base isolators. The essential feature of base isolation is to ensure that the period of the structure is well above that of the predominant earthquake input. The use of base isolators has become more practical with the successful development and inclusion of mechanical energy dissipators in the base isolators. An energy dissipator has the same function as a shock absorber in a car (i.e. its "soaks up" the energy of the excitation). These dissipators which are now being manufactured and used in the United States were developed by

the New Zealand Department of Scientific Industrial Research and extensively tested over a twelve year period. When used in combination the flexible isolation device an energy dissipator can control the response of the structure by limiting the displacements and forces, thereby, significantly improving seismic performance.

Mayes [37] also reports that the relative displacements are reduced to a practical design level of four to six inches. The seismic energy is dissipated in components specifically designed for that purpose relieving structural elements from energy dissipation roles and thus damage. There are three basic elements in any practical base isolation system. These are: (1) a flexible mounting so that the period of vibration of the total system is lengthened sufficiently to reduce the force response, (2) a damper or energy dissipator so that the relative deflections between building and ground can be controlled to a practical design level, (3) a means of providing rigidity under low (service) load levels such as wind and minor earthquakes.

The most compelling argument, according to Kelly and Hodder [38], for base isolation is the protection afforded internal equipment and piping. The response of non-structural components is determined primarily by the response of the primary structure to earthquake ground motion and not by ground motion itself. While the main structure of a building

or power plant can be protected from the damaging effects of an earthquake attack with relative ease, the necessary strengthening of the main structure increases the seismic loads transmitted to non-structural components and equipment.

4.4.2 Historical Background and Present Uses

Pan [34] states that base isolation has become a practical possibility with the recent development of multi-layer elastomeric bearings. Bearings for use in an aseismic isolation system are a natural development of bridge bearings and of acoustic isolation bearings. According to Pan, experience with bridge bearings for many years has demonstrated that they are reliable and resistant to environmental damage including that from oil and fire.

Kelly [35] states that the concept of base isolation is a natural one based on accepted physical principles. It has not, however, been readily accepted by the structural engineering profession because the concept runs counter to accepted measures of aseismic design. According to Kelly, the design codes in all countries with seismic regulations require that an earthquake attack be absorbed by a structural system through inelastic action. Inelastic action inevitably involves damage, however, not only to the structural system but also to non-structural components and essential equipment.

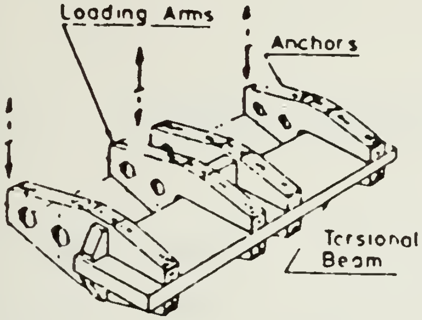
Furthermore, design calculations for the dynamic inelastic response of the building and of the contents to earthquake loading are extremely expensive. The standard approach is to design the building to survive by increasing structural strength and capacity to dissipate energy.

A form of multilayer elastomeric bearings is presently used as fenders on docks and wharves. Recognition of the engineering qualities of rubber has led to the use of elastomeric bearings in several buildings which have been built or are under construction with base isolation systems [33].

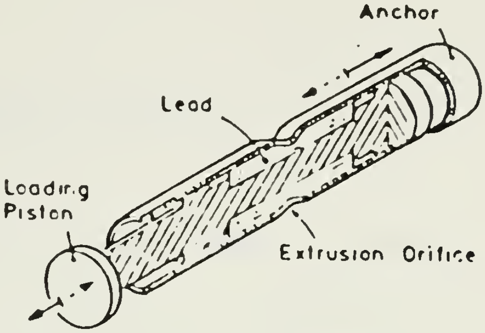
Dynamic Isolation Systems Inc. (D.I.S.), a manufacturer of dynamic isolators states in their literature [36] that 200 structures in 25 countries have been seismically isolated. Applications include buildings, bridges, and nuclear power plants. The eight lane Sierra Point overpass on Highway 101 near San Francisco Airport was protected in 1985 by D.I.S. lead-rubber bearings to decrease seismic forces transmitted to the bridge. This was the first base isolated bridge in the United States.

The first new building in the United States to employ seismic isolation was the Law and Justice Center in San Bernardino, California. This building underwent a 4.9 Richter scale magnitude earthquake on October 2nd 1985. The base

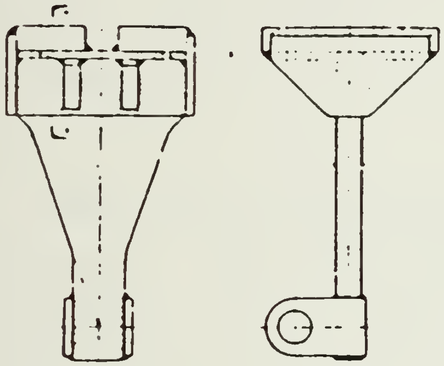
isolation system reduced the 0.04 g peak ground acceleration input to 0.03 g at the roof. Conventional fixed based buildings nearby amplified ground motion to a maximum of 0.15 g. The data was recorded by the California Strong Motion Instrumentation Program (CSMIP). Several mechanical dissipation devices have been developed as shown in figure (4.6) [37].



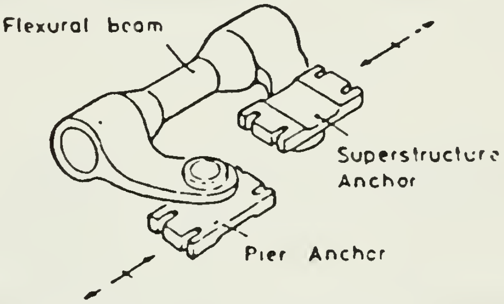
Torsional Beam Device



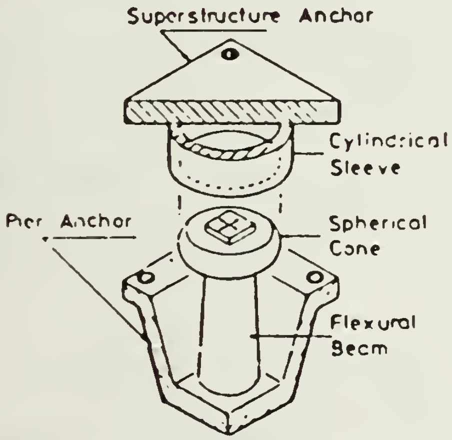
Lead Extrusion Device



Flexural Plate Device



Flexural Beam Device



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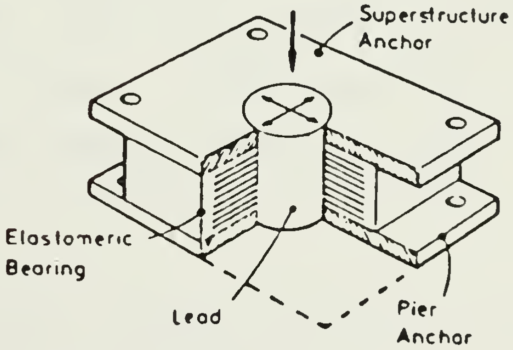


Lead—Rubber Device

Various Mechanical Energy Dissipators

FIGURE 4.6

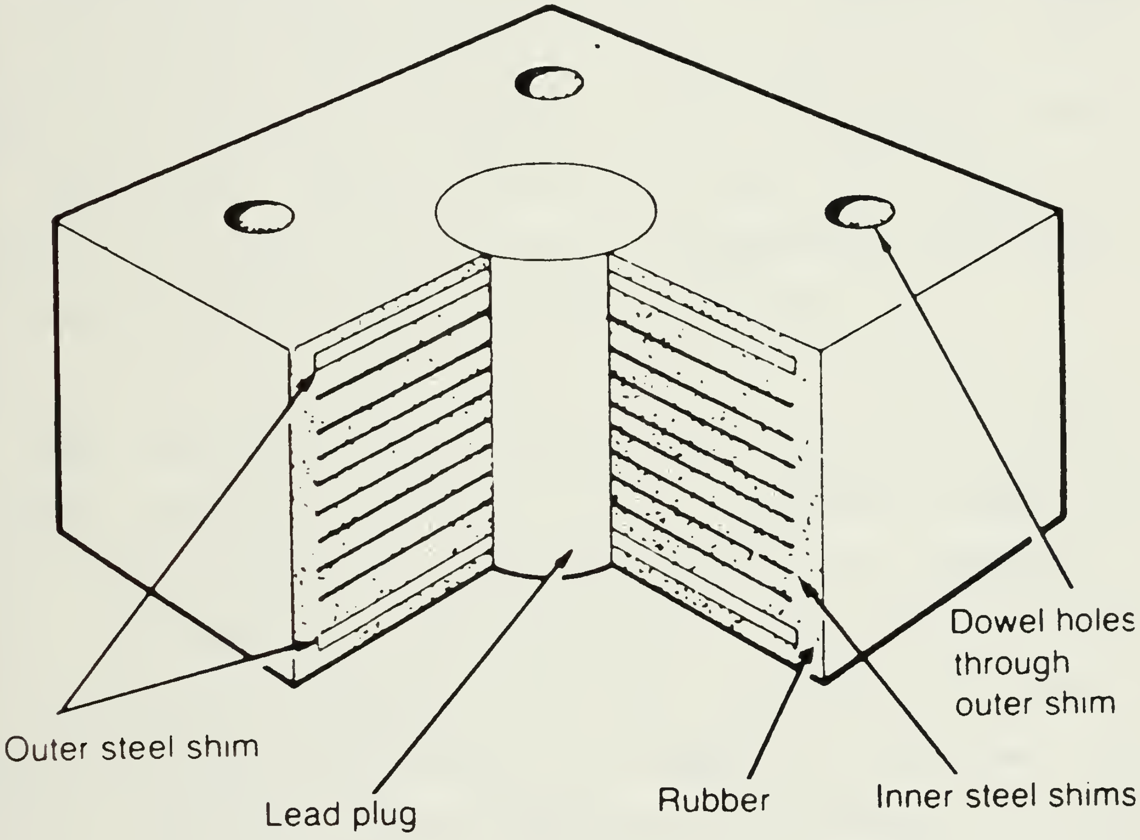
4.4.3 Dynamic Isolation System's Isolator

Description of the D.I.S. lead rubber bearing, the isolator used in this thesis, is shown in figure (4.7) [36]. The isolator is made of alternate layers of rubber and steel encased in a vulcanized rubber cover. The lead plug, which provides wind restraint and seismic damping, is fitted into the center.

While the introduction of lateral building foundation flexibility may be highly desirable additional vertical flexibility is not. Vertical rigidity in the D.I.S. isolator is maintained by constructing the rubber bearings in layers and sandwiching steel shims between each layer. The steel shims which are bonded to each layer of rubber constrain lateral deformation of the rubber under vertical load resulting in vertical stiffness several hundred times the lateral stiffness.

One of the most effective means of providing a substantial level of system damping is through hysteretic energy dissipation. The term hysteretic refers to the difference in the loading and unloading curves under cyclic loading.

THE DIS LEAD-RUBBER BEARING

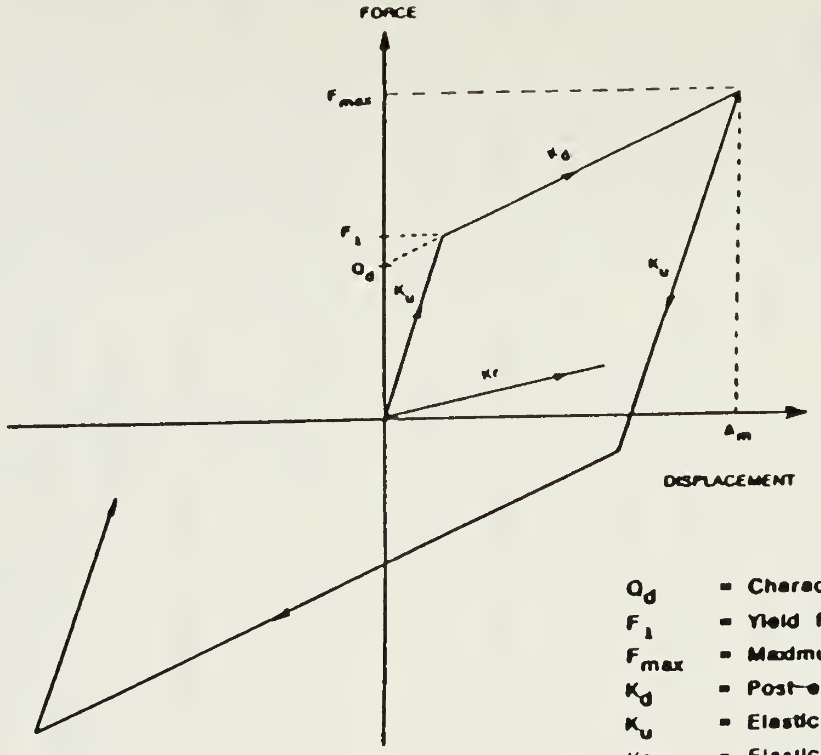


USA Patent No 4 117.637

FIGURE 4.7

Figure (4.8) [37] is a typical idealized force-displacement loop for the D.I.S. isolator. The inclosed area is a measure of theenergy dissipated during one cycle of motion. Lead, which is used as the mechanical damper in the D.I.S. isolator, is a crystalline material which changes its crystal structure under deformation but also instantly regains its original crystal restructure when the deformation ceases. For this reason, lead exhibits excellent hysteretic damping properties over many repeated cycles of earthquake motion. The lead rubber bearing provides the low load rigidity by virtue of the high initial elastic stiffness as illustrated by the initial elastic curve in figure (4.8) [37].

The analysis in this thesis will be limited to the D.I.S. isolator as shown in figure (4.7). According to Mayes [37] this is the most highly developed and practical dissipator to date. It combines in one physical unit the flexible element and the energy dissipator. In this application the lead is forced to deform plastically in shear by the steel shim plates. Excellent energy dissipation is possible with this device. Mayes reports that recent work by Kelly and Buckle at the University of California at Berkeley and also by Buckle at the University of Auckland in New Zealand has validated the performance of this device to the point where it can be used in practical applications with the same confidence as with other building materials such as steel or concrete.



Q_d = Characteristic strength (kips)
F_1 = Yield force (kips)
F_{max} = Maximum force (kips)
K_d = Post-elastic stiffness (kip/inch)
K_u = Elastic (unloading) stiffness (kip/inch) (=6.5K_d)
Kr = Elastic stiffness of rubber acting alone (Kip/inch)
Δ_m = Maximum bearing displacment

Lead-Rubber Bearing Properties

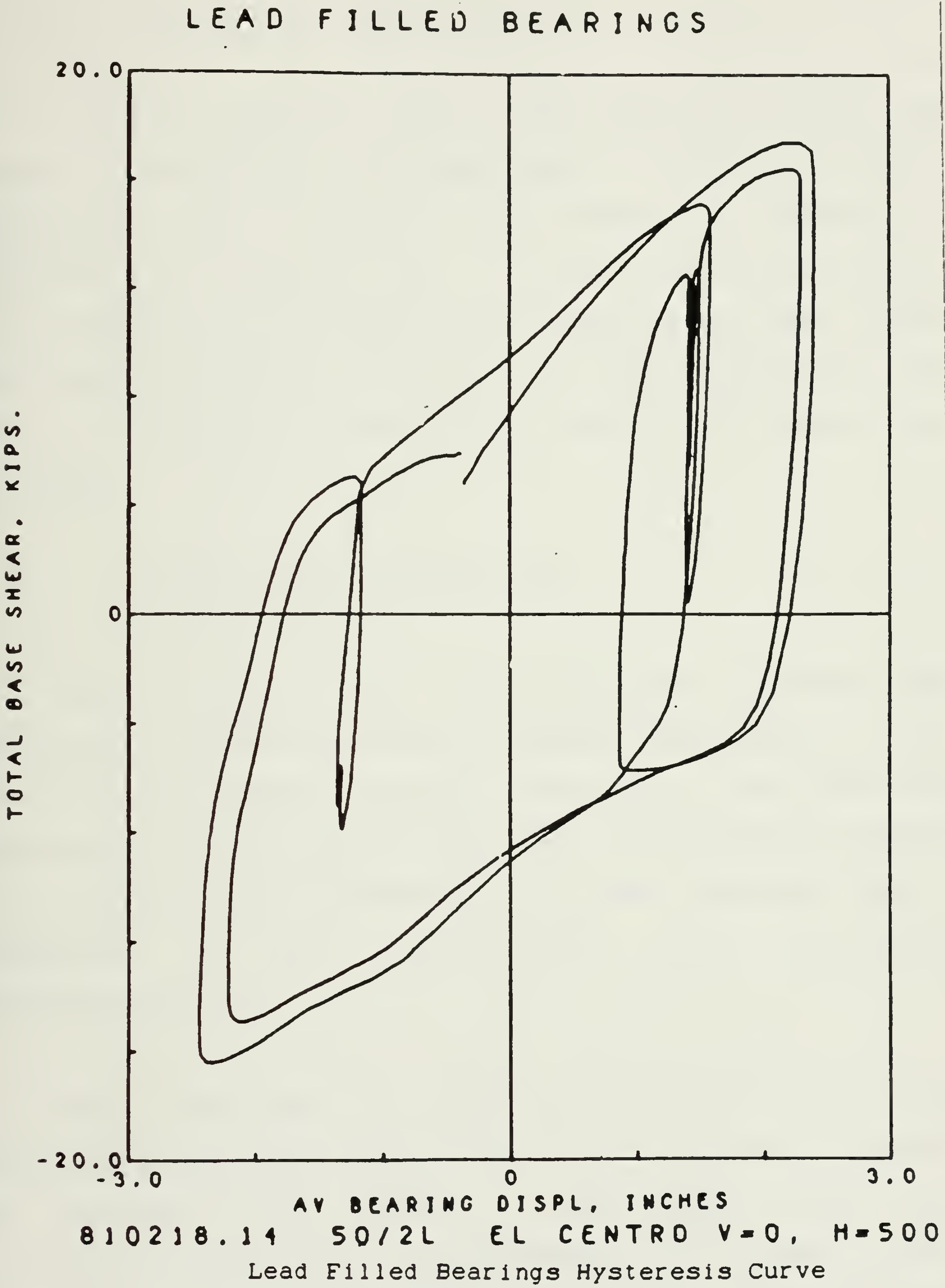
FIGURE 4.8

Design charts [37] have been developed for the D.I.S. isolators, and they can be built in a variety of sizes (footprint), rubber thicknesses, and lead plug sizes. The total rubber thickness for a given bearing footprint defines the degree of isolation provided to the structure. Mayes reports that it is most advantageous to use the rubber thickness corresponding to the longest effective period, if there are no constraints on the height of the bearings or bearing displacement. The thicker the rubber the more isolation and more lateral displacement. Once the desired rubber thickness is decided, the bearing construction (number and thicknesses of rubber layers) may be determined. The standard construction for a given total rubber thickness consists of 1/8 inch internal steel shims and 3/4 inch steel top and bottom plates. Charts have also been developed [37] as a means of rapidly arriving at a lead plug diameter for a given load. Lead plugs may be distributed over the bearings such that individual bearings may have differing yield levels.

Kelly and Hodder (1982) [38] carried out base isolation experiments on cylindrical lead filled laminated elastomeric bearings. The 1940 El Centro N00E acceleration time history as well as three other earthquakes time histories were used. Hysteresis loops for various filled and unfilled bearings were measured. A simulated five story building on these bearings was excited by a shaker table using the earthquake acceleration time histories.

A typical hysteresis curve for lead filled bearings subject to the El Centro earthquake is shown in figure (4.9) [38]. This exhibits the measured bilinear response characteristic of these bearings. The response of the structural model on the lead filled bearings is markedly different from that on unfilled or elastomer filled bearings. The lead appears to act as if it were almost perfectly plastic with a yield shear stress of approximately 1.4 kips/in^2 (9.6 kN/mm^2). As the lead yields significant energy dissipation occurs, in effect the lead acts as a mechanical fuse and an energy dissipator.

Kelly and Hodder describe the lead/bearing assembly of the D.I.S. isolator as an almost ideal isolation system. Their experiments showed that the bearings are capable of sustaining a relative lateral displacement of 75 % of their diameter without buckling. The reductions in maximum accelerations experienced by the supported building compared to conventionally designed structures vary with earthquake signal, but are not less than a factor of 10 and can be much higher.



Lead Filled Bearings Hysteresis Curve
from Experiments

FIGURE 4.9

4.4.4 Other Current Research

According to Kelly [35], other mechanisms have been tested in combination with elastomeric bearings including a mechanical fuse in the form of a notched pin designed to fracture at a specified level of shear force which acts as a wind restraint. A fail safe skid system has also been tested. This system produces a Coulomb frictional damping and in the event of earthquake ground motion, acts to prevent structural collapse.

4.4.5 Summary and Recommendations

Dominic Zegaint, head of the Structural Branch, Navy Facilities Engineering Command (NAVFAC), has stated that the Navy accepts seismic isolation as one of the techniques available to the structural engineer. He declared that NAVFAC is giving serious consideration to base isolation and is committed to its implementation under appropriate circumstances [36].

Kelly and Hodder [38] state that for nuclear plants the very low probability seismic events for which the plants must be designed could require a much higher design peak acceleration than could be accommodated by a simple rubber bearing base isolation system. The energy dissipating base isolation system in which rubber bearings and lead inserts are

integrated then becomes an ideal choice for seismic protection of these plants. No other structural design strategy can simultaneously protect a structure at such earthquake intensities and limit the forces applied to sensitive internal equipment.

The bearings themselves are not expensive items, particularly if many are manufactured. The cost of one type of lead filled elastomeric bearing is about $2000 each according to Kelly (1980) [35]. An elastomeric bearing is not the only means of introducing flexibility, but according to Mayes [37] it appears to be the most practical with the widest range of applications.

The use of dynamic isolators in submarine drydock blocking systems has tremendous potential. The footprint of these isolators can be made to be the same as existing drydock blocks. Luchs (1988) [21] determined that base isolators are one method of preventing failure of submarine drydock blocking systems during earthquakes. In this thesis, a method of modeling the effects of substituting the oak layer in submarine drydock blocking systems with D.I.S. isolators is developed.

4.5 Determination of Drydock Blocking Pier Stiffnesses

With the inclusion of many different types of materials in one side block or keel block pier, a method was needed to determine the horizontal and vertical pier spring constants. In this thesis, the piers are modeled in the horizontal direction as cantilever beams and shear elements. In the vertical direction they are modeled as axially loaded columns. In both directions they are considered to be composite elements with different properties along the length.

A LOTUS 1-2-3 spreadsheet was developed to calculate the stiffnesses. A sample vertical and horizontal set of spreadsheets are included in Appendix 2. These spreadsheets apply to a system similar to submarine blocking system number two. The spreadsheets were designed to be able to calculate pier stiffnesses with four block material layers. The example spreadsheets stiffness calculations are for a system with rubber, Douglas fir, oak, and concrete layers.

The first spreadsheet in Appendix 2 is the calculation of keel vertical stiffness. The procedure used was a standard addition of element stiffnesses in series as follows:

$$kvk' = 1/[(1/k_{rubber})+(1/k_{fir})+(1/k_{oak})+(1/k_{concrete})] \qquad (4.4)$$

Where kvk' is the stiffness of one keel pier. This required knowing each layer's dimensions and modulus of elasticity. This information was obtained from the appropriate submarine docking drawing. The stiffness of an individual layer is given by:

$$k = EA/L \tag{4.5}$$

E is modulus of elasticity of the layer.
L is the height of the layer.
A is the area over which the vertical force is applied.

For some layers the cross-sections varied over the layer or there were abrupt transitions from one layer to the next. In these cases an effective area was used based on the standard 1 to 3 load distribution slope employed by the Naval Sea Systems Command. Figure (4.10) illustrates how this effective area is determined.

This procedure was used to calculate the stiffness of one individual keel pier. To determine the stiffness of the entire keel system the individual keel pier stiffness was multiplied by the number of keel blocks. Side pier vertical stiffnesses were determined in a similar manner.

The second spreadsheet in Appendix 2 is the calculation of keel horizontal stiffness for this same four layered system.

Blocking Pier Stiffness Effective Area

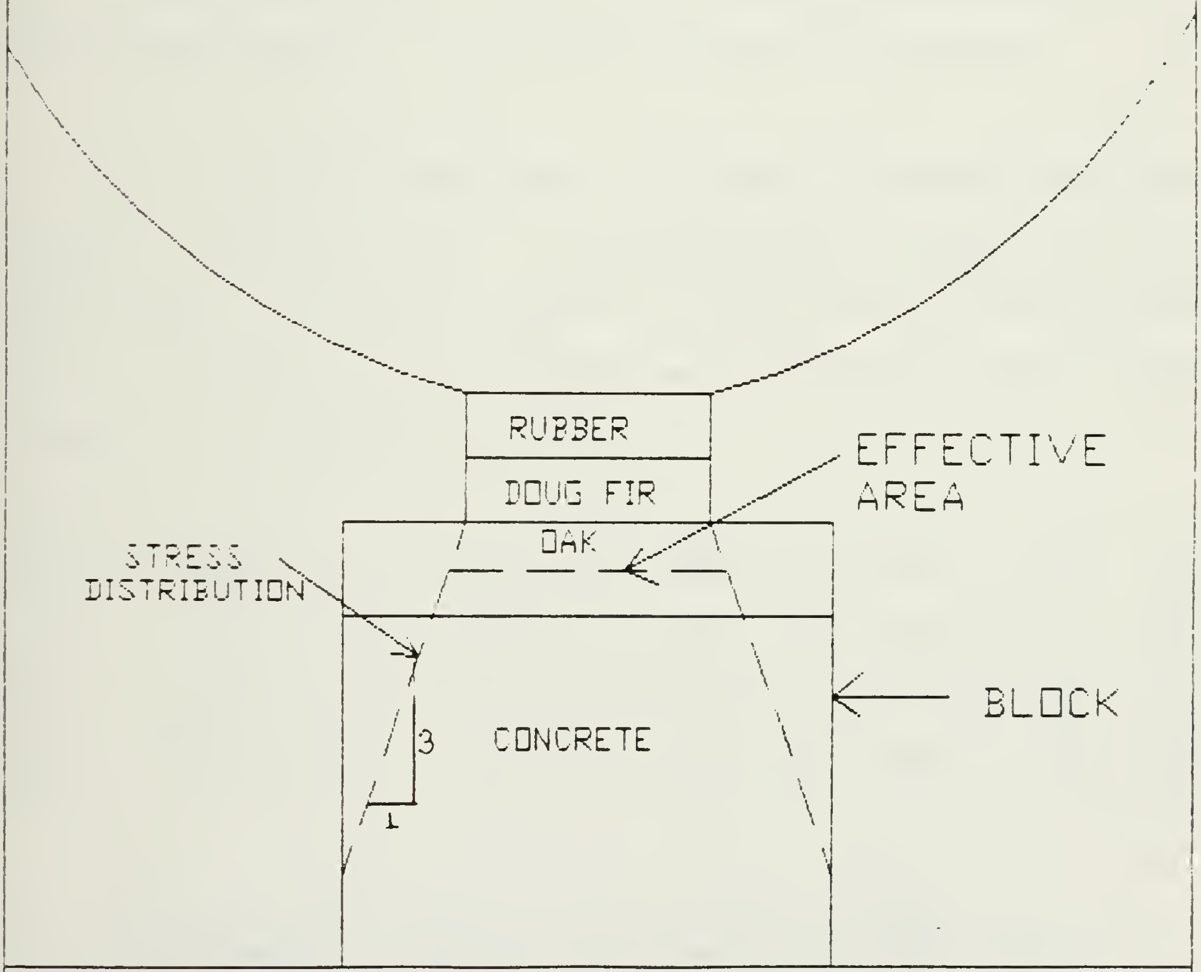


FIGURE 4.10

For the computation of horizontal stiffness, two types of horizontal deformation must be considered: the horizontal cap displacement due to bending and the horizontal cap displacement due to shear. The total keel pier stiffness coefficient for one keel pier (khk') is then given by:

$$khk' = P/(d_b+d_s) \tag{4.6}$$

Where P is the horizontal force applied to surface of the cap. d_b is the displacement of the cap's surface due bending and d_s is the displacement of the cap's surface due to shear.

In the case of bending, the block is modeled as a four element cantilever beam. The displacement of the top of this beam due to the applied force P is determined by the stiffness matrix method. The stiffness matrix equation for the first element is as follows:

$$\begin{bmatrix} Q_1 \\ M_1 \\ Q_2 \\ M_2 \end{bmatrix} = \begin{bmatrix} 12E_1I_1/L_1^3 & 6E_1I_1/L_1^2 & -12E_1I_1/L_1^3 & 6E_1I_1/L_1^2 \\ 6E_1I_1/L_1^2 & 4E_1I_1/L_1 & -6E_1I_1/L_1^2 & 2E_1I_1/L_1 \\ -12E_1I_1/L_1^3 & -6E_1I_1/L_1^2 & 12E_1I_1/L_1^3 & -6E_1I_1/L_1^2 \\ 6E_1I_1/L_1^2 & 2E_1I_1/L_1 & -6E_1I_1/L_1^2 & 4E_1I_1/L_1 \end{bmatrix} \begin{bmatrix} q_1 \\ \theta_1 \\ q_2 \\ \theta_2 \end{bmatrix} \tag{4.7}$$

E_1 is the modulus of elasticity of element number 1.
I_1 is the moment of inertial of element 1's cross section.
L_1 is the length of element 1.
Q's are the nodal forces.
M's are the nodal moments.
q's are the nodal displacements.
θ's are the nodal rotations (radians).

The elemental stiffness matrix equations are determined in a similar fashion for elements 2, 3, and 4. They are then combined to form a ten by ten stiffness matrix as shown in the horizontal stiffness spreadsheet in Appendix (2). The combined stiffness matrix equation is then solved to determine the displacement (d_5) at the top of the beam due to force P. Because Q_1 and M_1 are known and $q_1 = \theta_1 = 0$, by equilibrium solving the 10 by 10 matrix reduces to solving four two by two matrices. This was accomplished in the spreadsheet by using Cramer's rule.

In shear the block is modeled as a composite element subject to shear stress at the top of each layer. For element 1 the following equation holds:

$$\gamma_1 = (P/A_1)/G_1 \qquad (4.8)$$

γ_1 is the shear strain in element 1
P is the horizontal force acting on the surface of element 1.
G_1 is the modulus of rigidity of element 1.
A_1 is the top contact area.

The following formulas were used used in this thesis to determine the moduli of rigidity for the layer materials:

Element 1 (concrete) $G = 0.6E$ [26] (4.9)

Element 2 & 3 (D.fir and oak) $G_R = (1/14)E_L$ [26] (4.10)

Element 4 (rubber) $G = 0.339E$ [30] (4.11)

The value of the top contact area, A, was the actual dimensions of the top of the layer if there was complete contact with the layer above. If the footprint of the upper layer was smaller, then the top contact area was assumed to be approximately the average of the footprint area and the actual top area of the layer.

The shear displacement was determined using the following equation:

$$d_s = \gamma_1 L_1 + \gamma_2 L_2 + \gamma_3 L_3 + \gamma_4 L_4 \qquad (4.12)$$

The total horizontal horizontal stiffness for a row of blocks is the value of khk' times the number of keel blocks. Similar spreadsheets were used employing four layers to determine the side block pier horizontal stiffnesses.

CHAPTER 5

WOOD BILINEAR MATERIAL PROPERTY MODEL

5.0 Determination of Blocking Wood Properties

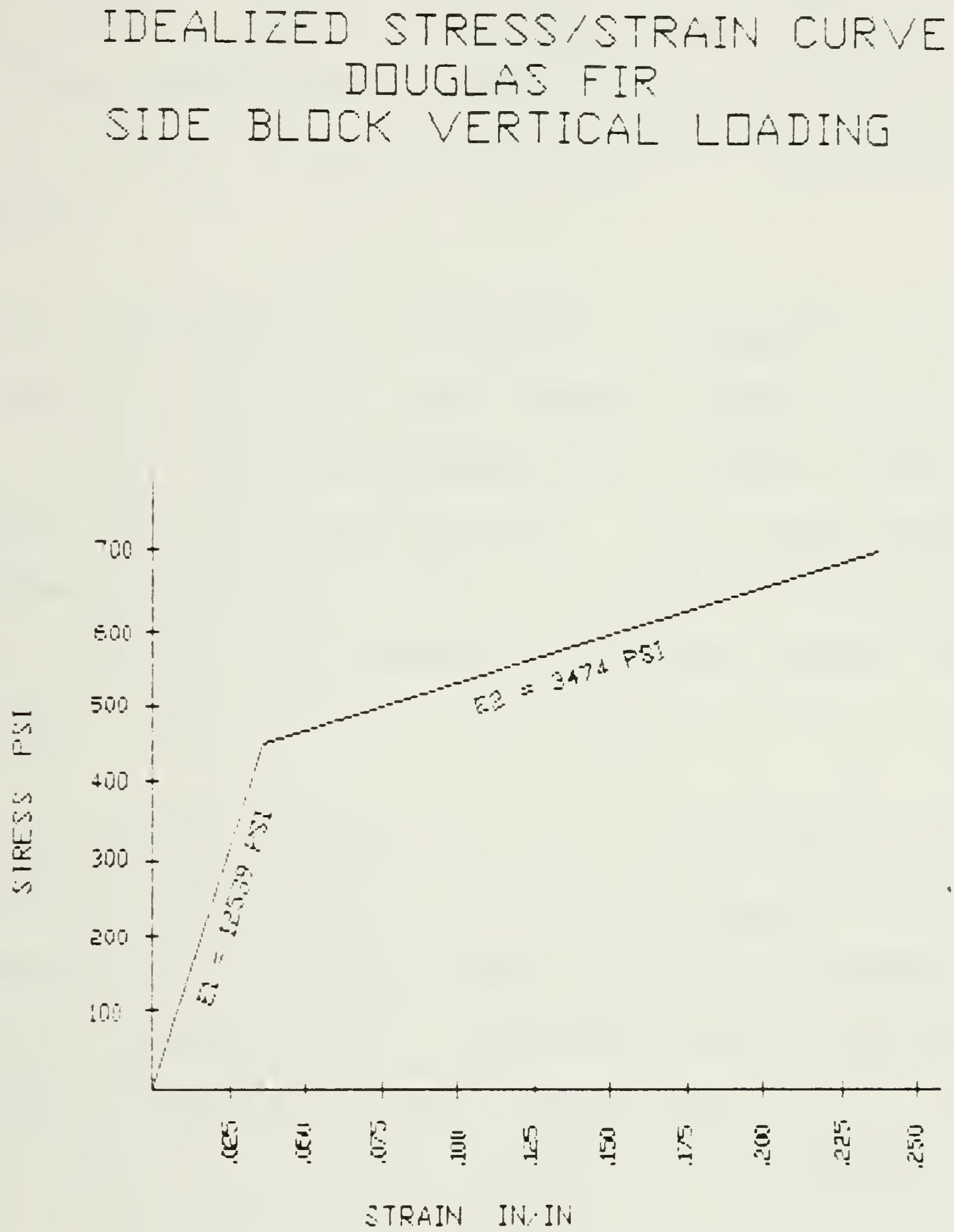
As shown previously, Douglas fir and oak used in U.S. Navy drydock blocking systems are non-linear anisotropic materials. Their properties are functions of many different variables. For this thesis, the Douglas fir caps are modeled as bilinear materials. This means that up to the FSPL the Douglas fir has an initial constant modulus of elasticity. When subject to additional stress, the wood undergoes plastic deformation and the modulus of elasticity changes to a lesser value. This modulus is in effect until ultimate stress (about 700 psi) is reached. This model for Douglas fir is based on the compressive stress-strain curve illustrated in figure (4.5) [22]. The two moduli obtained from measuring the slopes off this figure are E1 = 12539 psi and E2 = 3474 psi.

Test results from the University of Washington study [22] gave an average FSPL for Douglas fir timbers of 367 psi. This value was for a test loading which occurred over a period of about five minutes. As shown before, the FSPL of wood varies with the duration of loading. Using an average earthquake load cycle of one second and applying a correction factor of 1.23 obtained from figure (4.4) [27], an earthquake loading FSPL of 450 psi is calculated. From these values an idealized

stress-strain curve for Douglas fir in the side blocks subject to vertical loading is constructed. This is illustrated in figure (5.1).

Due to the anisotropic nature of Douglas fir the FSPL and modulus of elasticity are dependent on grain orientation relative to the applied force. As Bodig showed, the ratio between modulus parallel to the grain, E_L, and modulus perpendicular to the grain, E_T, is about 20 : 1. For vertical loading of the side blocks the force is almost perpendicular to the grain. For system 1 this cap angle is 68.4 degrees. For horizontal loading this angle is 21.6 degrees. Typically, blocking timbers used in shipyards include "circled hearts" and other irregularities. For this reason the orthotropic model needs to be modified somewhat. As a conservative approximation, a value for E_L/E_T of 14 is used. This coincides with the ratio of parallel to perpendicular compressive strength shown in figure (4.3) [23]. This figure is used to modify the modulus of elasticity of both Douglas fir and oak to account for orientation of the grain relative to applied force.

As shown in figure (5.1), the values for side block modulus for vertical loading is assumed not to be affected by the 68.4 degree load angle with the grain. Figure (4.3) is very flat between 60 to 90 degrees, therefore the perpendicular values are used.



IDEALIZED STRESS/STRAIN CURVE
DOUGLAS FIR
SIDE BLOCK VERTICAL LOADING

FIGURE 5.1

For horizontal loading, grain orientation has a very large effect. In this case, the perpendicular values of E1 and E2 are multiplied by a factor of 7.6 obtained from figure (4.3) to obtain the horizontal values E1 = 95297 psi and E2 = 26398 psi.

In the horizontal direction, the strength of the Douglas fir caps is limited by their shear strength parallel to the grain. From the Wood Handbook [26] a value of 930 psi is obtained for this shear strength. From these values, the idealized stress-strain curve for Douglas fir in the side blocks subject to horizontal loading, figure (5.2), is obtained.

In the case of Douglas fir in the keel blocks, the horizontal applied force is exactly parallel to the grain, therefore, the correction value of 14 is applied. This results in values of E1 = 175549 psi and E2 = 48629 psi. The idealized stress-strain curve for Douglas fir in the keel blocks subject to horizontal loading is illustrated in figure (5.3).

Oak is assumed to stay linear. Oak is generally stiffer and the Douglas fir cap areas are smaller and thus subject to higher stresses. However, grain orientation corrections are applied to the oak similar to the Douglas fir corrections.

IDEALIZED STRESS/STRAIN CURVE
DOUGLAS FIR
SIDE BLOCK HORIZONTAL LOADING

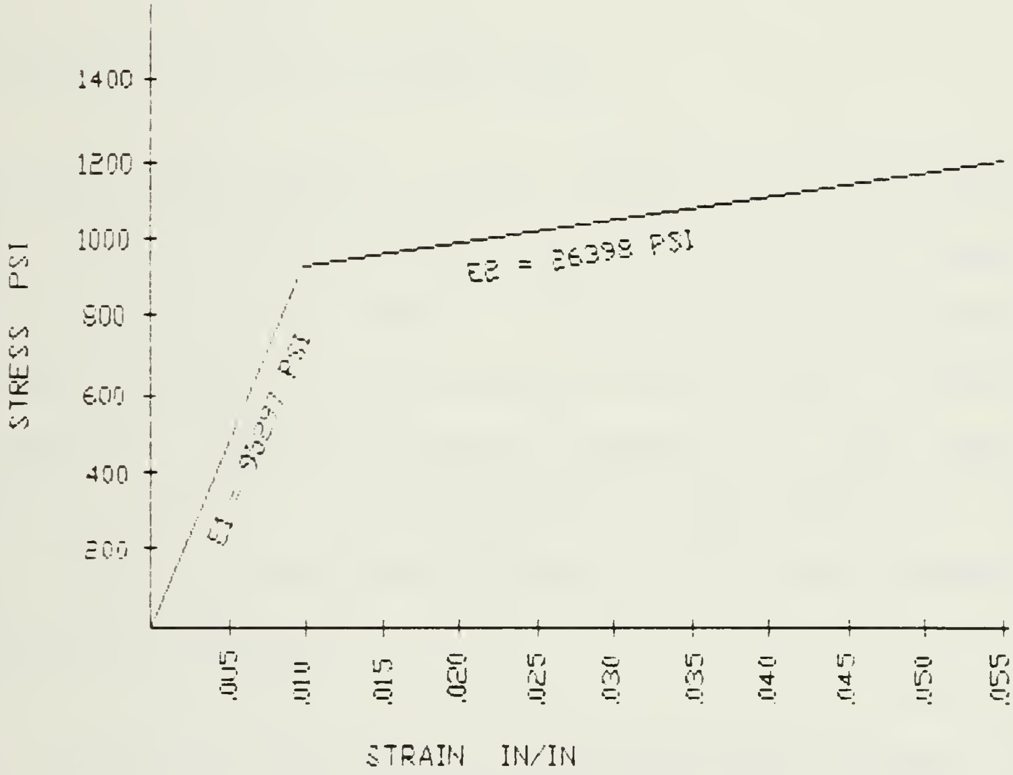


FIGURE 5.2

The modulus of elasticity value used in all cases for vertical loads on oak is 23980 psi obtained from blocking material test data [22]. For horizontal loads the modulus value for oak for keel blocks and side blocks is 335720 psi. Cap angle is assumed to not effect the oak. The oak layer is assumed to be perpendicular to the vertical loads and parallel to the horizontal loads.

5.1 Keel Block System Bilinear Model

Sigman [16] assumed in his research that the submarine drydock blocking systems failed when the Douglas fir caps were loaded beyond their FSPL. This is an unnecessarily restrictive assumption that does not allow taking into account the hysteretic damping effects produced by wood when it plastically deforms. The Douglas fir caps actually remain intact up to a stress beyond 700 psi. This is well beyond the assumed FSPL of 450 psi.

If the blocks are assumed to survive past the FSPL, a new way of modeling the block stiffness other than linear elastic needs to be developed. One way of modeling this behavior is called elasto-plastic. This model is described by Biggs (1964) [39] and Paz (1986) [40]. This model assumes that after the material is loaded past its proportional limit, it becomes purely plastic with stiffness equal to zero. The

material unloads with exactly the same slope (stiffness) as it is loaded.

This elasto-plastic model is fairly close to the behavior of wood; however, as seen in figure (5.3) the stiffness of the Douglas fir in the keel block system does not go to zero past the FSPL. Therefore, the elasto-plastic model must be modified to more closely match the behavior of the Douglas fir.

A curve which matches the behavior of Douglas fir more closely is that of the D.I.S. dynamic isolator shown in figure (4.8). This behavior is called bilinear. Figure (5.4) is an illustration of this model as applied to the horizontal keel blocking system. The entire keel blocking system is assumed to exhibit bilinear behavior. However, all the materials in the keel blocking system are assumed to remain linear-elastic except the Douglas fir which changes its modulus of elasticity as illustrated in figure (5.3) once its FSPL is exceeded. Generally, the Douglus fir caps are small and subject to higher stresses than the larger oak sections of the pier. By inputting these two values for modulus into the horizontal stiffness spreadsheets described earlier (Appendix 2), two values for the keel blocking system horizontal stiffness are obtained.

IDEALIZED STRESS/STRAIN CURVE
DOUGLAS FIR
KEEL BLOCK HORIZONTAL LOADING

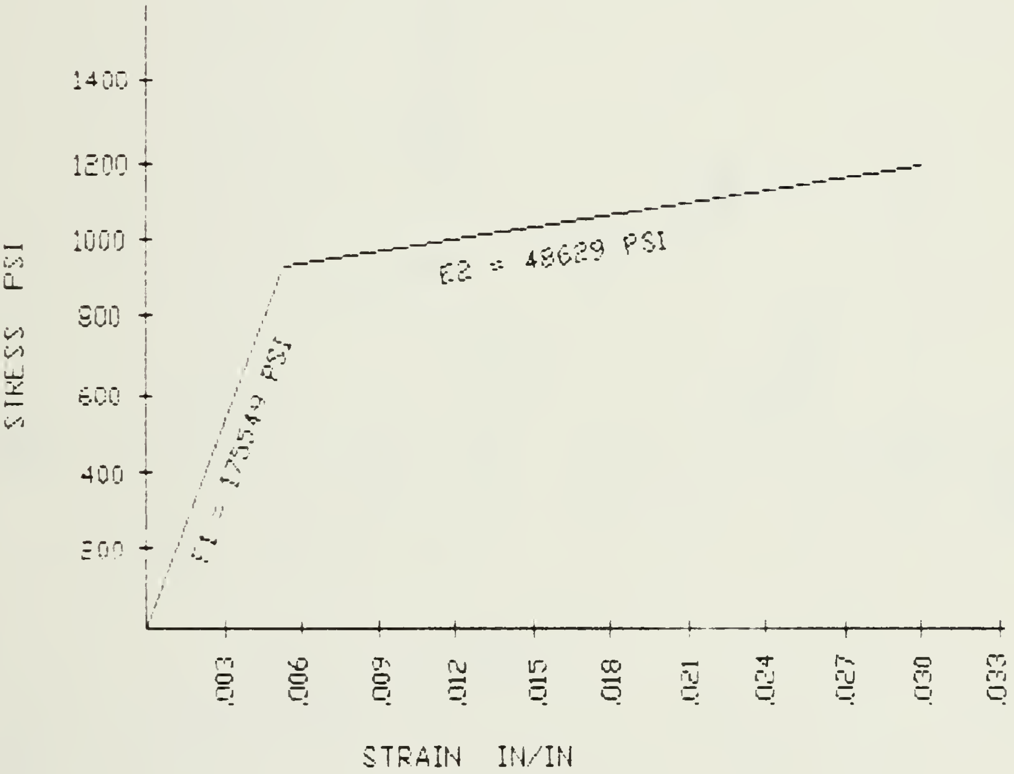


FIGURE 5.3

BILINEAR FORCE/DISPLACEMENT CURVE
FOR
HORIZONTAL KEEL BLOCKING SYSTEM

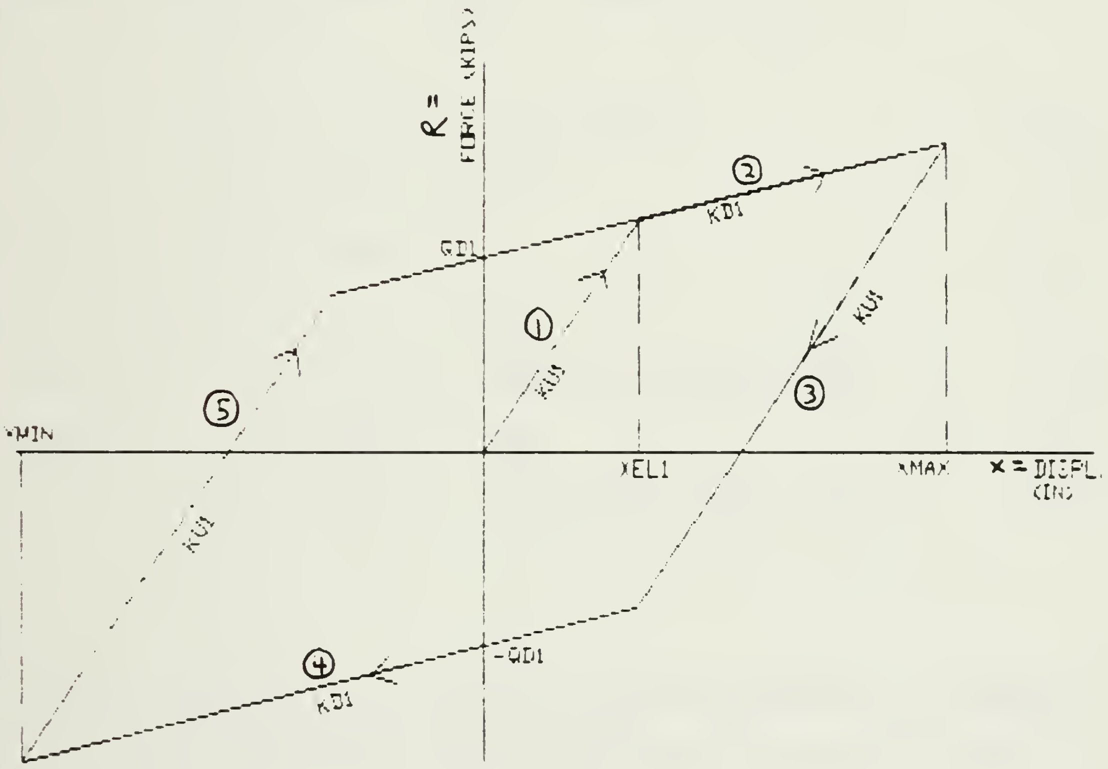


FIGURE 5.4

These two values are khk = 59223 kips/in and khkp = 38435 kips/in where khk is the initial elastic stiffness value and khkp is the stiffness after the system has been loaded past the FSPL.

In figure (5.4), KU1 is equal to khk and KD1 is equal to khkp. In this figure, and throughout this thesis the terminology used in figure (4.8) and by Buckle (1987) [41] is followed. The following equations describe the various features of the bilinear loop in figure (5.4):

$$XEL1 = P/khk = \tau_s A_s/khk \tag{5.1}$$

$$QD1 = XEL1(KU1-KD1) \tag{5.2}$$

$$\text{Line 1:} \quad R = KU1*x \tag{5.3}$$

$$\text{Line 2:} \quad R = KD1*x + QD1 \tag{5.4}$$

$$\text{Line 3:} \quad R = KU1*x + (KD1-KU1)*XMAX + QD1 \tag{5.5}$$

$$\text{Line 4:} \quad R = KD1*x - QD1 \tag{5.6}$$

$$\text{Line 5:} \quad R = KU1*x + (KD1-KU1)*XMIN - QD1 \tag{5.7}$$

Where:

XEL1 is the elastic limit for the blocking system in inches.

τ_s is the maximum shear stress parallel to the grain for Douglas fir.

As is the keel blocking system cap area.

R is the restoring force of the keel blocking system due to horizontal deformation.

x is the horizontal displacement of the cap surface of the keel blocking system.

XMAX is the horizontal displacement of the cap surface at the point when where the bilinear loop shifts from line 2 to line 3. This is the point when the velocity of the keel blocking system cap changes from positive to negative during earthquake excitation. The blocking system then unloads elastically down line 3 with slope KU1.

XMIN is the horizontal displacement of the cap surface at the point when the loop shifts from line 4 to line 5. This is the point when the velocity of the keel blocking system cap changes from negative back to positive during earthquake excitation. The blocking system then unloads elastically up line 5 with slope KU1.

A similar procedure is developed to calculate horizontal side block system stiffnesses and vertical side block system stiffnesses. In the vertical case there are some differences. First, the submarine weight causes an initial vertical static deflection in the keel and side blocks. This is taken into account by using a "DELTA" value, the static vertical deflection. "DELTA" changes as the block system stiffness changes and is updated for each time step in the three degree of freedom submarine drydock blocking system program, "3DOFRUB". The incorporation of the "DELTA" value into this computer program is discussed by Luchs [21] in greater detail. The other difference is that in the vertical direction there is no restoring force once the submarine lifts off of the side blocks. The model breaks down at this point and the computer

program flags this as a failure mode. Therefore, only the upper right hand quadrant of the bilinear loop is valid for vertical loading of the side blocks. Lift off occurs if there is zero vertical restoring force.

These procedures are then used to determine the keel and side block horizontal and vertical stiffnesses for all eleven submarine drydock blocking systems. Table (5.1) lists these stiffnesses for each system. KVSP, which is equal to KD3, is the vertical side block stiffness once the vertical FSPL has been exceeded. Similarly, KSHP, which is equal to KD2, is the horizontal side block stiffness once the horizontal FSPL has been exceeded. A complete listing of system (1-11) stiffnesses and values for XEL, QD, KU, KD are included in Appendix 3.

The area inside the bilinear loop is the energy lost to the system due to hysteretic damping during one excitation cycle. Figure (5.4) is an idealized picture of what would occur during one cycle of earthquake excitation. It is typical of what would happen during sinusoidal excitation where the FSPL is exceeded. However, earthquake excitation is much more complex and random in nature. The actual bilinear plot for an earthquake excitation is much more complicated.

TOTAL KEEL AND SIDE PIER STIFFNESS KIPS/IN
BILINEAR SYSTEMS (1-11) PER DOCKING DRAWINGS

SYSTEM	KVK	KVS	KVSP	KHK	KKHP	KHS	KSHP
1	46808.74	10113.39	4025.64	59223.08	38434.86	5825.13	2212.17
2	46808.74	5231.06	2082.23	59223.08	38434.86	3013.00	1144.23
3	31919.89	6178.56	3211.52	28875.45	22849.71	4055.29	1897.66
4	31919.89	3195.81	1661.13	28875.45	22849.71	2097.56	981.55
5	46808.74	3195.81	1661.13	59223.08	38434.86	2097.56	981.55
6	83270.20	43011.07	22269.52	79683.44	53718.39	28797.14	13345.17
7	83270.20	28512.95	14762.94	79683.44	53718.39	19090.24	8846.80
8	83270.20	21747.17	11259.87	79683.44	53718.39	14560.35	6747.56
9	24375.19	8629.57	4065.53	22050.35	17448.87	5842.63	2409.17
10	19442.11	6808.09	3188.10	17587.78	13917.55	4625.36	1890.63
11	19442.11	5236.99	2452.39	17587.78	13917.55	3557.97	1454.33

TABLE 5.1

A BASIC computer program is developed to generate bilinear stiffness for any point in time during system excitation. This program is general in nature so it can handle random earthquake excitations. It is developed based on an elasto-plastic BASIC program developed by Paz [40]. A listing of this program is included in Appendix 3. It includes a detailed explanation of the logic used to compute the bilinear stiffnesses. This program is later translated into FORTRAN and is included as a subroutine in "3DOFRUB". The name of this subroutine is "BILINALL" and is included in Appendix 1.

5.2 System 1 Bilinear Analysis Results

System 1 parameters are entered into "3DOFRUB" and the following results are obtained. First, the system fails at 16 % of the 1940 El Centro Earthquake due to side block liftoff. A copy of the output of this run and input data file are included in Appendix 3.

The system does not deform plastically in the horizontal direction. However, plastic deformation of the side block caps does occur in the vertical direction. Figure (5.5) shows the restoring force, R4, as a function of time. R4 is designated as the force on the right set of side blocks looking forward at the submarine blocking system.

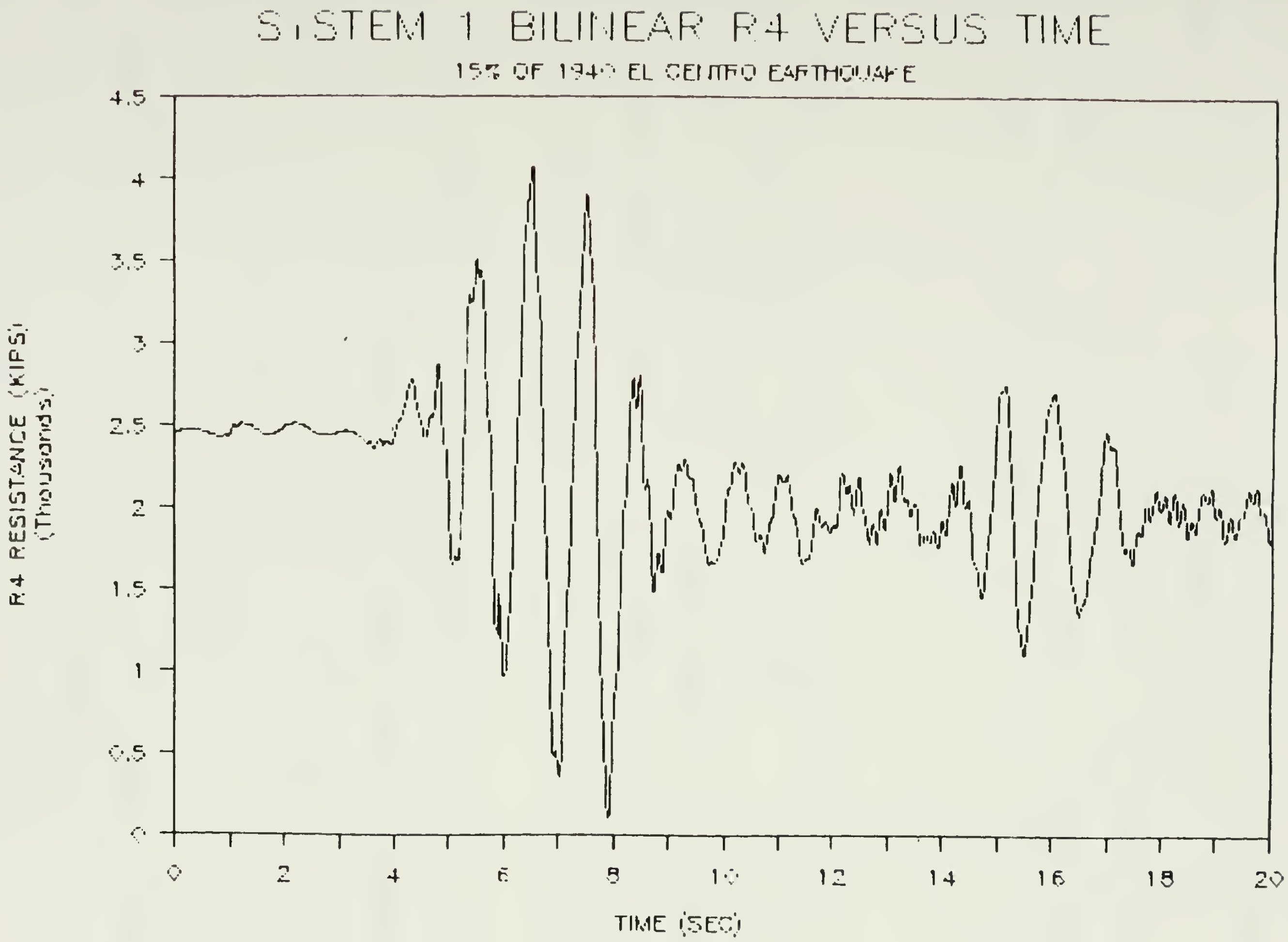

SYSTEM 1 BILINEAR R4 VERSUS TIME
15% OF 1940 EL CENTRO EARTHQUAKE
R4 RESISTANCE (KIPS)
(Thousands)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
16
18
20
TIME (SEC)

FIGURE 5.5

R4's initial value is a measurement of the portion of the weight of the submarine supported by that set of side blocks. Initially, it is excited about this point. After plastic deformation of the cap occurs, the right set of side blocks incurs a permanent set; therefore, the keel blocks, which do not plastically deform, are deflected to the same point as the side blocks and take more of the load. This reduces the load on the side blocks and causes the R4 plot to oscillate around a new lower value.

Figure (5.6) is a plot of the rotation of the submarine about the keel during this earthquake. There is direct correlation between rotation magnitude and R4 throughout much of the earthquake. This illustrates the dominance of the rotational degree of freedom in this particular system.

The permanent set is most evident in figure (5.7). This plot of R4 versus YPRIME2 (side block vertical deflection) is the upper right quadrant of the bilinear loop. Since this is a plot of the response to 15 % of the 1940 El Centro Earthquake, which the system survives, the plot remains in this quadrant and R4 does not go below zero. However, this plot does indicate that failure is imminent. A permanent set of 0.06 inches can be seen.

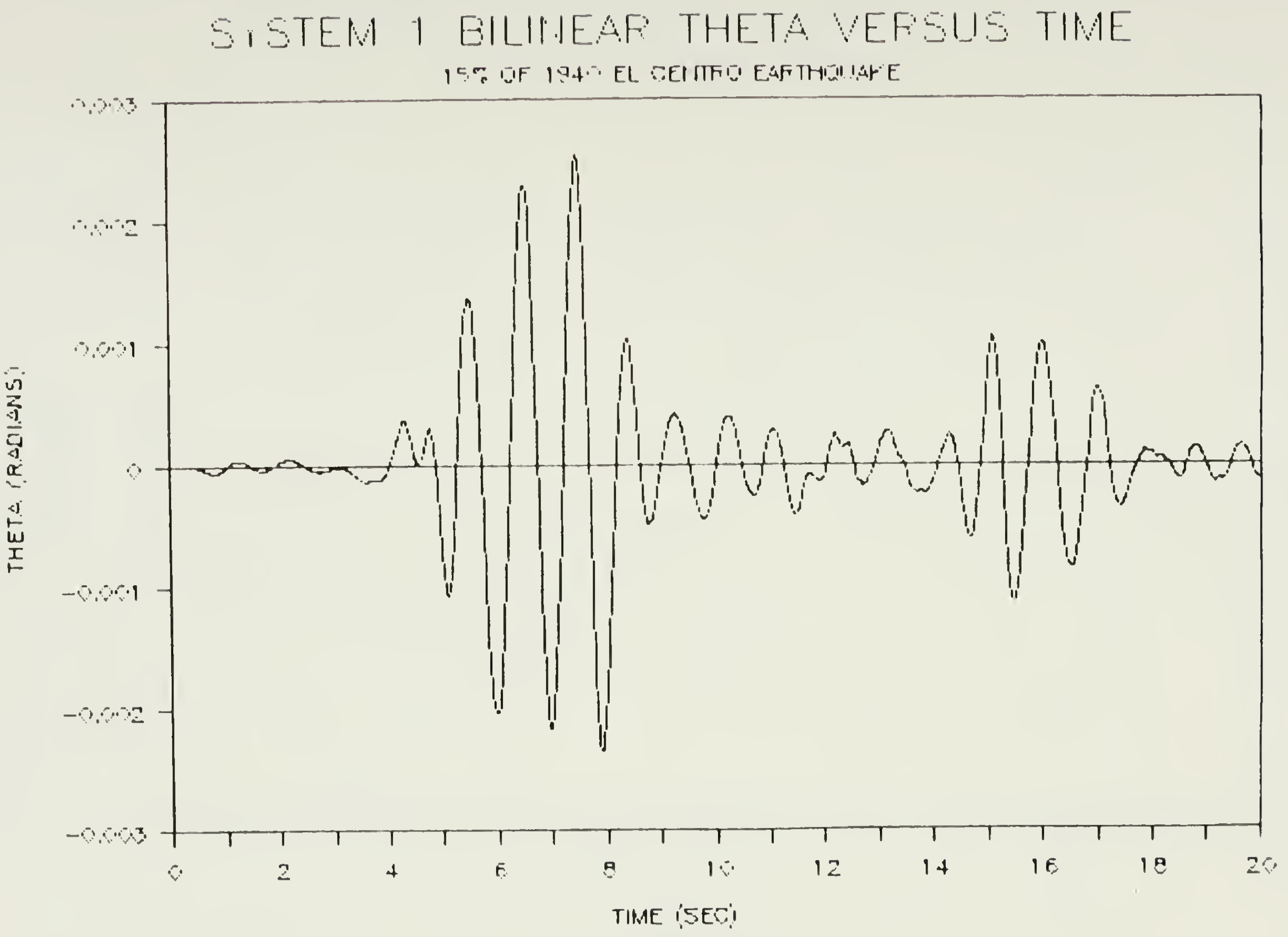

SYSTEM 1 BILINEAR THETA VERSUS TIME
15% OF 1940 EL CENTRO EARTHQUAKE
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
THETA (RADIANS)
0
2
4
6
8
10
12
14
16
18
20
TIME (SEC)

FIGURE 5.6

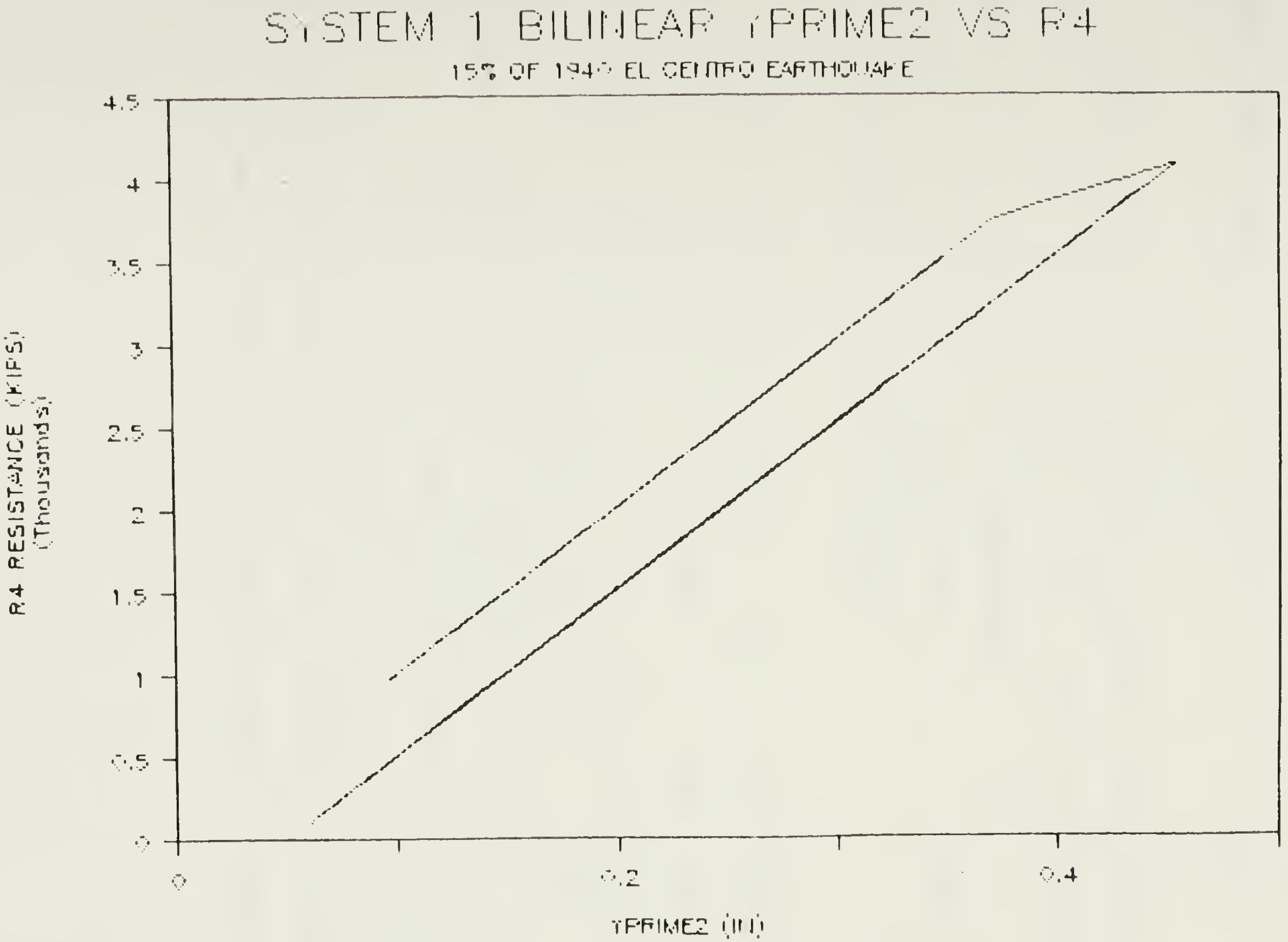

SYSTEM 1 BILINEAR YPRIME2 VS R4
15% OF 1940 EL CENTRO EARTHQUAKE
R4 RESISTANCE (KIPS)
(Thousands)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
0.2
0.4
YPRIME2 (IN)

FIGURE 5.7

Failure would occur earlier because the location of the actual side block surface has changed. Lift off would occur at this new lower position. The bilinear behavior of the side blocks is clearly seen in the figure. The two stiffness slopes are evident.

Figure (5.8) is a plot of YPRIME during the 15 % of El Centro. The initial value is the static deflection of the side blocks. The zero displacement line on this curve indicates the initial undeflected position of the side blocks before the submarine weight is added.

Figure (5.9) is typical of the bilinear behavior due to horizontal loading of the keel or side blocks due to earthquake loading. One of the features of the bilinear subroutine logic is that as the velocity of the earthquake suddenly changes and the amplitudes decrease for a short period, the curve oscillates along an elastic line. Many of these oscillations can be seen in figure (5.9). This response is considered reasonable and is confirmed by experimental results done for dynamic isolators as shown in figure (4.9).

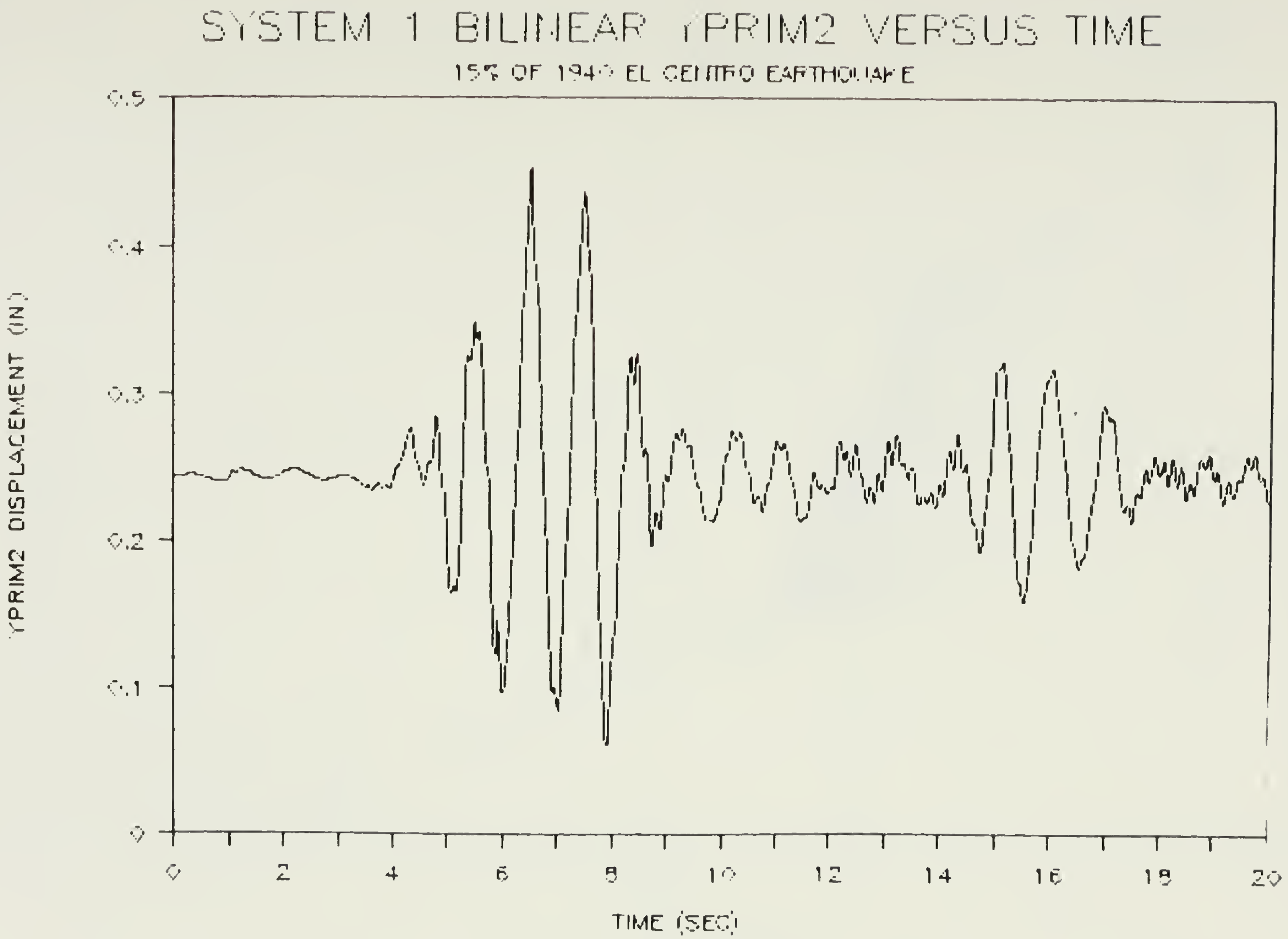

SYSTEM 1 BILINEAR YPRIM2 VERSUS TIME
15% OF 1940 EL CENTRO EARTHQUAKE
YPRIM2 DISPLACEMENT (IN)
0.5
0.4
0.3
0.2
0.1
0
0
2
4
6
8
10
12
14
16
18
20
TIME (SEC)

FIGURE 5.8

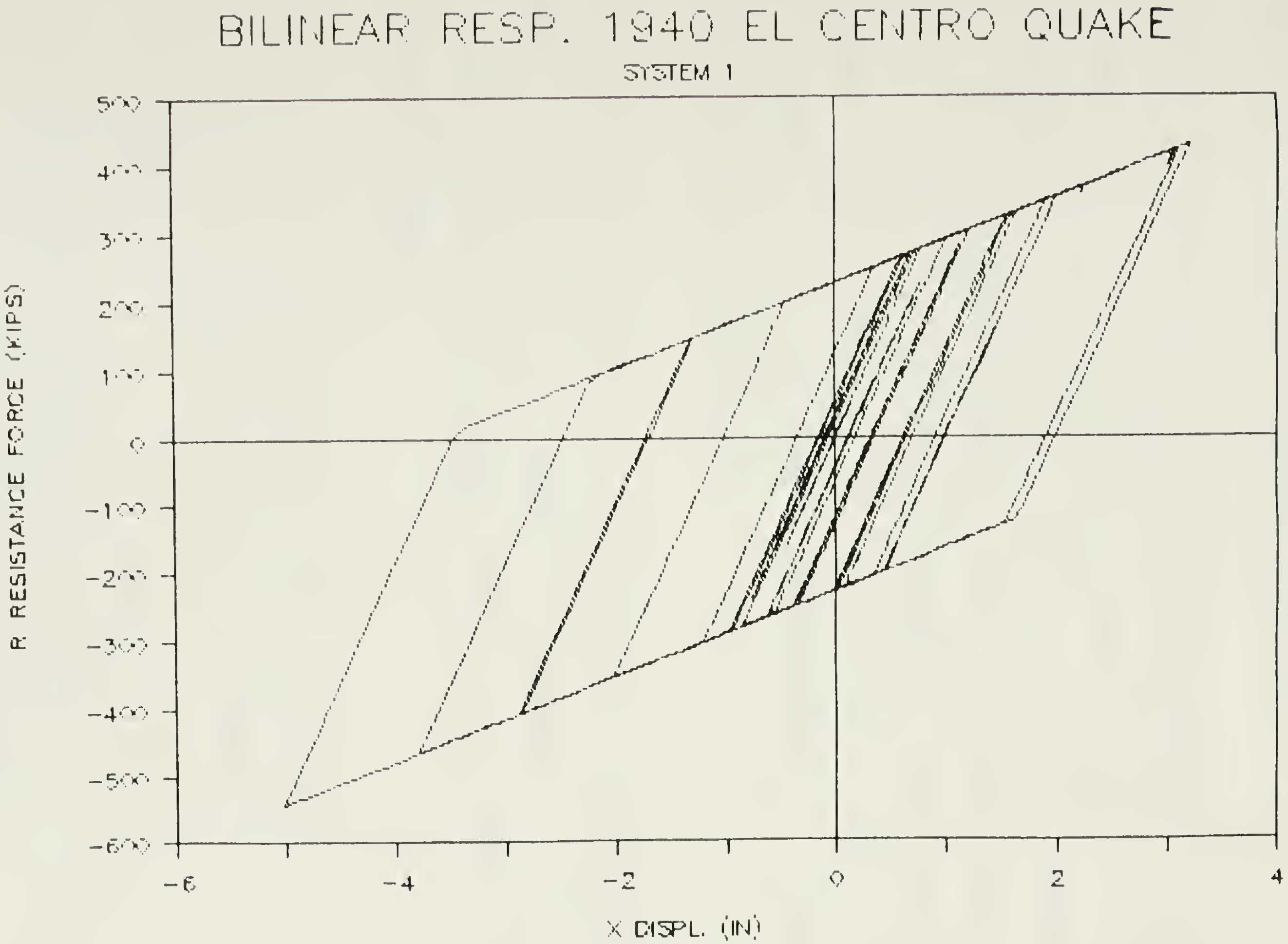

BILINEAR RESP. 1940 EL CENTRO QUAKE
SYSTEM 1
R RESISTANCE FORCE (KIPS)
500
400
300
200
100
0
-100
-200
-300
-400
-500
-600
X DISPL. (IN)
-6
-4
-2
0
2
4

FIGURE 5.9

CHAPTER 6

RUBBER BILINEAR MATERIAL PROPERTY MODEL

6.0 Determination of Rubber Cap Properties

As shown previously, rubber has many properties that make it an ideal capping material for drydock blocking systems. Though rubber is a non-linear material, it is possible to model it as a bilinear material using similar procedures as for wood. Based on data from compression tests conducted by the Johnson Rubber Company of Middlefield, Ohio [33] on natural rubber, a bilinear model is developed. These tests results are shown in figure (6.1).

Two lines are drawn on figure (6.1) to approximate the non-linear load deflection behavior measured. From these lines two values of bilinear modulus of elasticity are computed as follows:

$$\sigma_v = P_v/A = (25\ \text{kips})/(36*7\ \text{in}^2) = 99.2\ \text{psi} \qquad (6.1)$$

$$k_1 = P_v/y' = (25\ \text{kips})/(0.2\ \text{in}) = 125\ \text{kips/in} \qquad (6.2)$$

$$k_1 = E_1*A/L \qquad (6.3)$$

Combining (6.2) and (6.3) gives:

$$E_1 = k_1*L/A = (125\ \text{kips/in})*(2\ \text{in})/(36*7\ \text{in}^2) = 992.1\ \text{psi} \qquad (6.4)$$

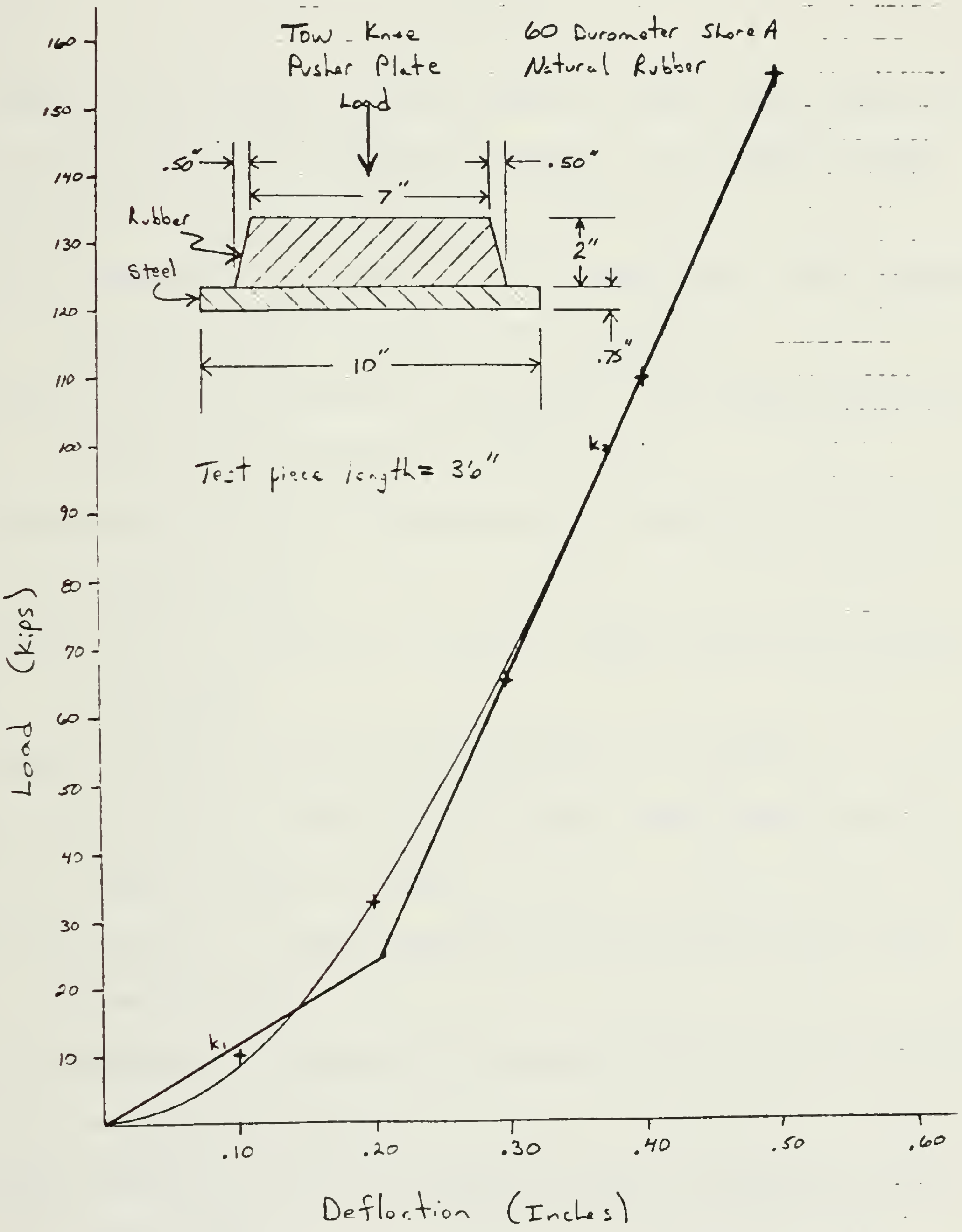
JOHNSON RUBBER CO.

SKETCHES AND COMPUTATIONS

JOB NO. ______

TITLE Load Deflection Test DATE ______

Turn in with job – make orderly and with notes so anyone can follow.



Rubber Compression Test Results and Bilinear Approximation

FIGURE 6.1

For the second slope:

$k_2 = \Delta P/\Delta y$ = (110-65 kips)/(0.4-0.3 in) = 450 kips/in (6.5)

$E2 = k_2 * L/A$ = (450 kips/in)*(2 in)/(36*7 in^2) = 3571 psi (6.6)

Where:

σ_y is the yield stress for the natural rubber in figure (6.1) at which point the modulus changes to a higher value.

P_y is the yield load for this test specimen.

A is the cross sectional area of the test piece. The specimen was 36 inches long by 7 inches wide.

k_1 is the initial stiffness of the rubber specimen which is the initial slope in figure (6.1).

y' is the deflection of the specimen at the point where the slopes change.

E1 is the initial modulus of natural rubber calculated from this test.

L is the thickness of the test specimen (2 inches).

k_2 is the second stiffness of the rubber specimen which is the second slope in figure (6.1).

ΔP is the change in load measured along a portion of the second slope.

Δy is the change in deflection measure along the same portion of the this slope.

E2 is the second modulus of natural rubber calculated from this test.

The initial value of modulus determined from this test specimen (992 psi) correlates very well with other compressive tests [30] conducted on hard rubber giving a modulus of 1044 psi.

Using the two computed moduli and the yield stress for natural rubber, an idealized stress-strain curve for natural rubber for side block vertical loading is constructed. This curve is shown in figure (6.2). This differs from the idealized stress-strain curve for Douglas fir in that rubber starts off initially with a low stiffness and shifts to a higher one at a relatively low stress level. Whereas, Douglas fir exhibits an initial high stiffness and shifts to a second stiffness similar to natural rubber at a much higher stress level.

Since rubber is isotropic, no load orientation modifications has to be made. As mentioned in section 4.3, up to very large values of strain, shear remains very close to linear and does not exhibit the change in stiffness as in the case of compression. Therefore, the modulus of rigidity and thus horizontal stiffness is assumed constant. Applying equation(4.11), the value of shear modulus of rigidity is computed as follows:

$$G = 0.339 * E1 = 0.339 * 992.1 \text{ psi} = 336 \text{ psi} \qquad (6.7)$$

IDEALIZED STRESS/STRAIN CURVE
NATURAL RUBBER
SIDE BLOCK VERTICAL LOADING

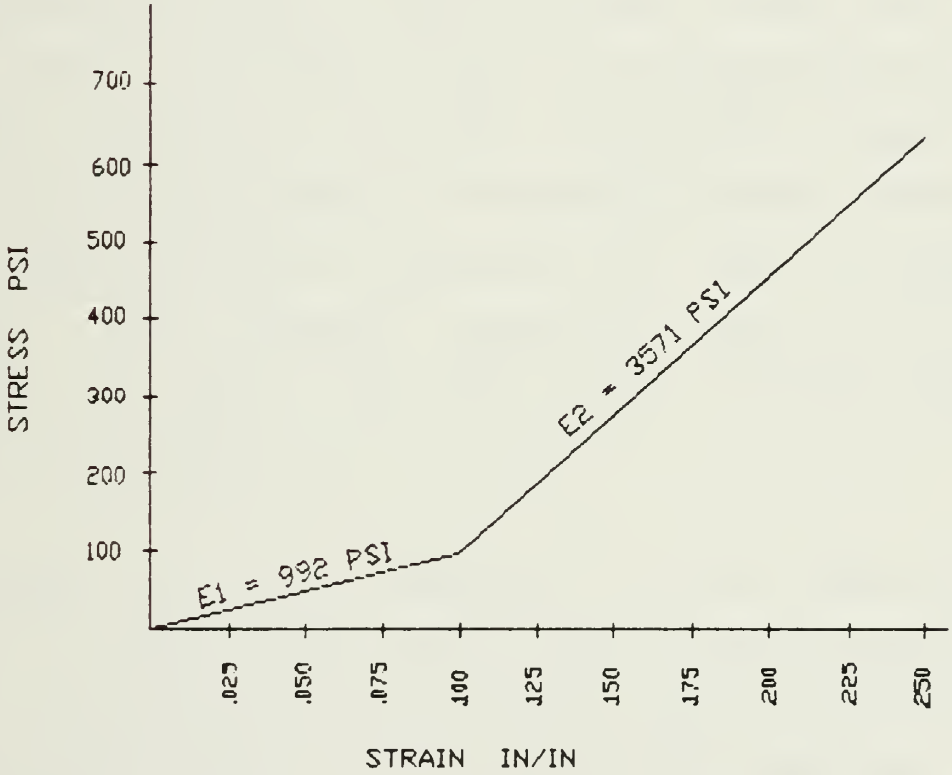


FIGURE 6.2

6.1 Side Block System Rubber Cap Bilinear Model

A modified form of the bilinear model used to represent Douglas fir is used for side block rubber caps under vertical loading. In the vertical direction, there is no restoring force once the submarine lifts off the side blocks; therefore, only the upper right hand quadrant of the bilinear loop is valid in this case. This rubber bilinear model differs from the Douglas fir model in that the rubber unloads down the same path that it is loaded. This is a good approximation of the behavior of rubber since rubber experiences no permanent set even past the point where it changes stiffness. Actual rubber does experience slight hysteresis, but this is taken into account in the "3DOFRUB" program by using 5 % critical damping. For very thick rubber caps 8 % critical damping is used in this thesis.

Figure (6.3) is a depiction of this rubber bilinear model. In this figure KU3 is equal to kvs and KD3 is equal kvsp. In this case, kvs is the total initial stiffness of one set of side blocks. It is obtained by inputting *E1* for natural rubber into the vertical stiffness spreadsheets included in Appendix 4. Similarly, kvsp is obtained by inputting *E2* for natural rubber into the vertical stiffness spreadsheets. The value kvsp is the total stiffness of one set of side blocks once the rubber cap changes stiffness to its higher value.

BILINEAR FORCE/DISPLACEMENT CURVE
RUBBER CAPS
SIDE BLOCKS VERTICALLY LOADED

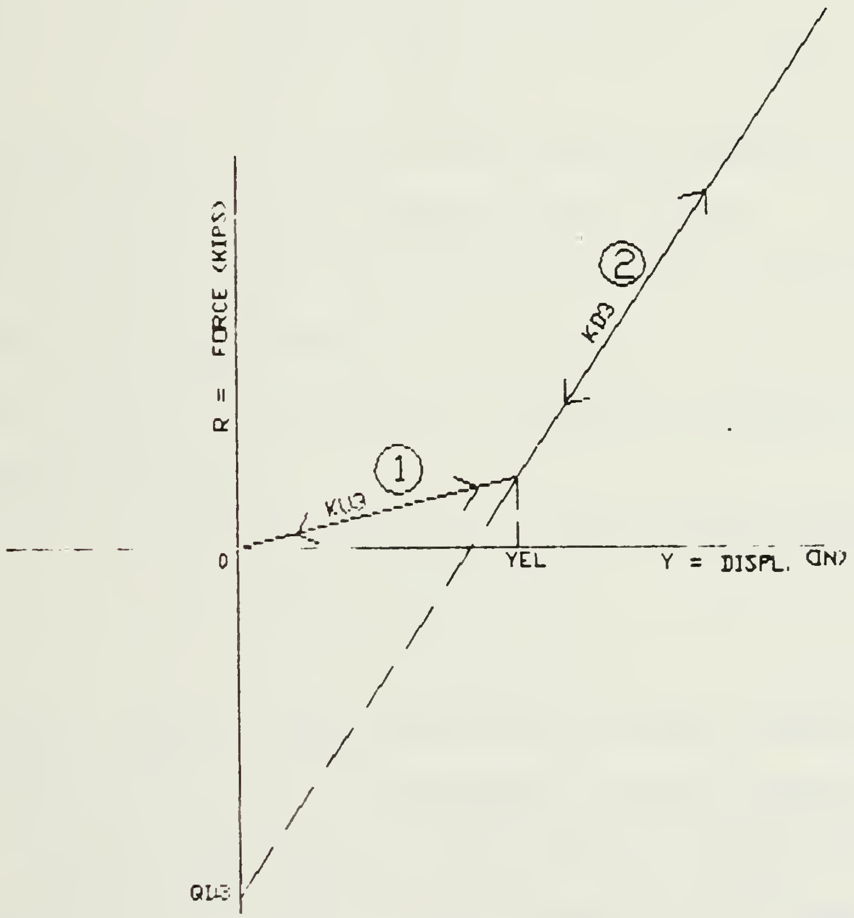


FIGURE 6.3

The following equations describe the various features of figure (6.3):

$$YEL = \sigma_y * A_c / kvs \tag{6.8}$$

$$QD3 = YEL * (KU3 - KD3) \tag{6.9}$$

Line 1: $$R = KU3 * y \tag{6.10}$$

Line 2: $$R = KD3 * y + QD3 \tag{6.11}$$

Where:

YEL is the elastic limit for the blocking system in inches.

A_c is the cap area for one set of side blocks.

R is the restoring force of the side blocking system due to vertical displacement.

y is the vertical displacement of the cap surface of the side blocking system.

QD3 is the R intercept of the second stiffness slope.

Since natural rubber exhibits bilinear behavior at a very low stress level, it is necessary to also develop a bilinear model for the keel blocks. This is not necessary for Douglas fir capped keel blocks because they do not reach sufficient stress levels to exhibit bilinear behavior. An approach similar to that used for the side blocks is used to develop the bilinear rubber model for the keel blocks.

An additional subroutine for the "3DOFRUB" computer program is developed to include the rubber bilinear behavior. This subroutine is called "RUBBER" and is included in Appendix 1. The "3DOFRUB" computer program uses the fact that the QD's are negative for rubber as a flag to call the "RUBBER" subroutine. The inclusion of both the "BILINALL" and "RUBBER" subroutines in "3DOFRUB" makes the program sensitive to materials with different types of non-linear behavior.

6.2 Rubber Bilinear Analysis Results

A one inch rubber cap is put on all of the eleven submarine drydock blocking systems. The stiffnesses are calculated using similar spreadsheets to those included in Appendix 4. The tabulated results for stiffnesses, YEL's, KU's, KD's, and QD's for these new systems are also listed in this appendix. System 12 corresponds to system 1 with a 1 inch rubber cap on both the keel and side blocks. Systems 30 through 39 correspond to systems 2 through 11 with similar rubber caps. Chapter 8 of this thesis compares the differences in response due to addition of rubber for all eleven systems.

System 12 parameters are entered into "3DOFRUB" and the following results are obtained. First, the system fails at 33 % of the 1940 El Centro Earthquake due to side block lift off.

Without the 1 inch rubber cap system 1 fails at 16 % of this earthquake. Therefore, the addition of 1 inch of rubber doubled the survivability of system 1. A copy of the output of the system 12 run and a copy of the input data file are included in Appendix 4.

Figure (6.4) is a plot of the restoring force, R4, as a function of time. As in the case of wood, R4's initial value shows the portion of the submarine weight supported by that set of side blocks. Unlike the wood case, no permanent plastic deformation of the cap occurs, and R4 oscillates about the initial displacement point. Again in this figure, as is the case for wood, the rotational degree of freedom appears to dominate the response for the side blocks. A plot of the rotation of the submarine about the keel as a function of time is shown in figure (6.5).

The rubber bilinear behavior of the side block system is clearly seen in figure (6.6). This figure shows that the rubber capped side blocks load and unload on the same curve during each cycle of the earthquake. Since this system survives this magnitude of the earthquake the value of R4 does not go below zero, however, failure is imminent.

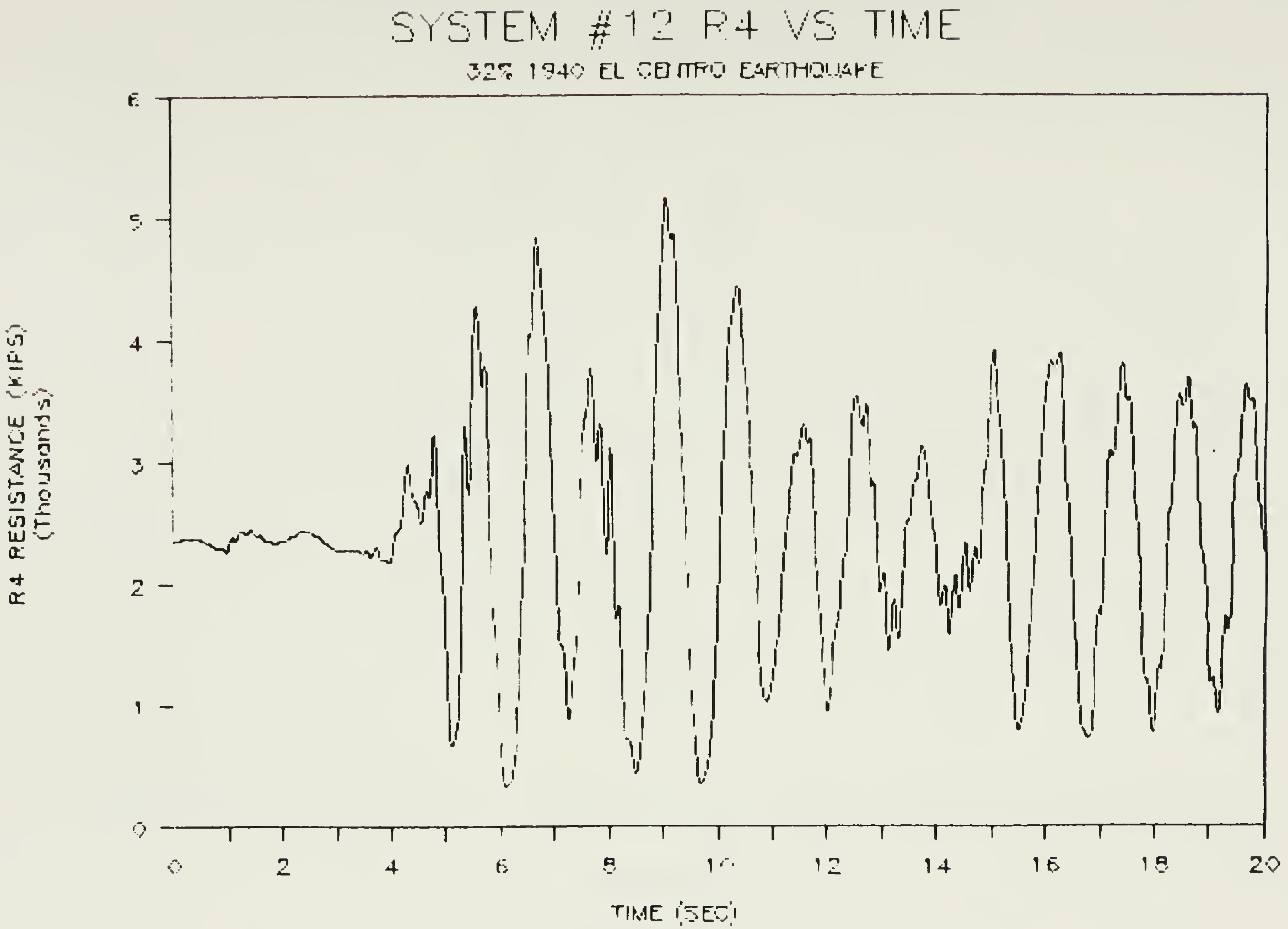

SYSTEM #12 R4 VS TIME
32% 1940 EL CENTRO EARTHQUAKE
R4 RESISTANCE (KIPS)
(Thousands)
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
16
18
20
TIME (SEC)

FIGURE 6.4

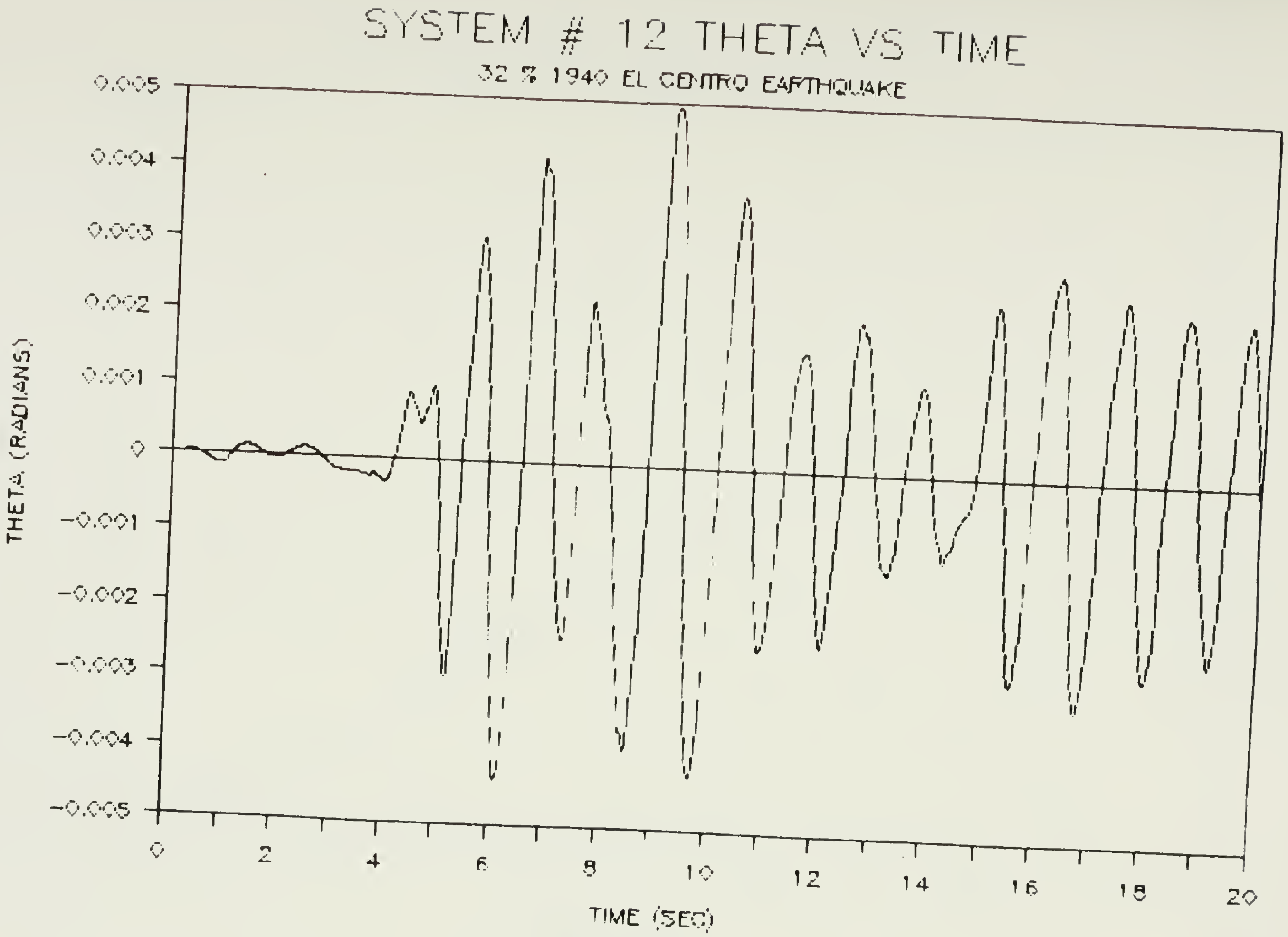

SYSTEM # 12 THETA VS TIME
32 % 1940 EL CENTRO EARTHQUAKE
THETA (RADIANS)
0.005
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
-0.005
0
2
4
6
8
10
12
14
16
18
20
TIME (SEC)

FIGURE 6.5

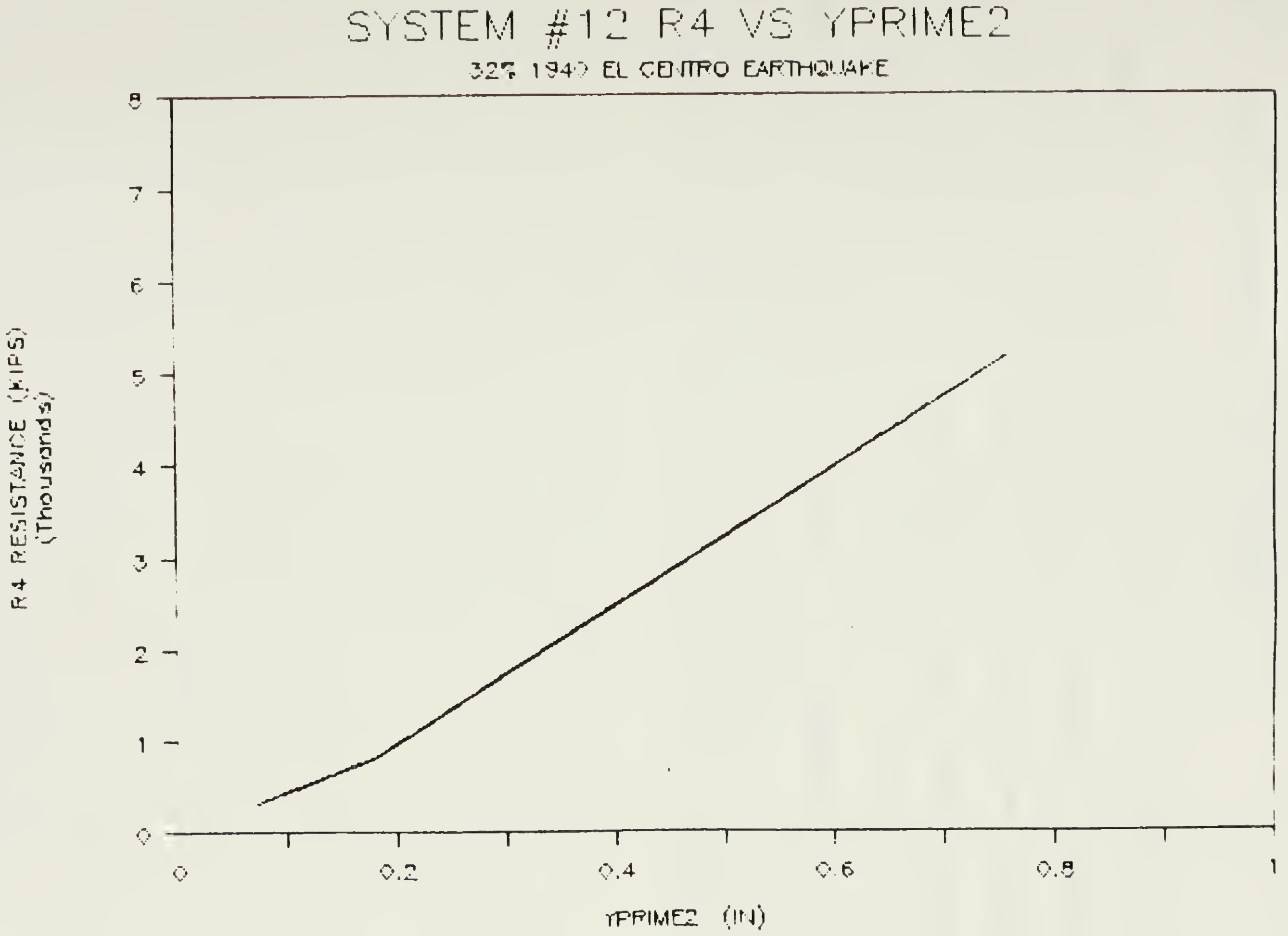

SYSTEM #12 R4 VS YPRIME2
32% 1940 EL CENTRO EARTHQUAKE
R4 RESISTANCE (KIPS)
(Thousands)
0
1
2
3
4
5
6
7
8
0
0.2
0.4
0.6
0.8
1
YPRIME2 (IN)

FIGURE 6.6

The key feature of the rubber capping material is displayed in figure (6.6). As the side block system unloads it becomes more difficult for the submarine to lift off the blocks as R4 and YPRIME2 approach zero. This is due to the rubbers' low stiffness at low stress.

Figure (6.7) is a plot of the vertical deflection of the side blocks during the earthquake. The initial deflection is the static deflection caused by the submarine weight. This initial deflection is significantly larger than the deflection which occurs when wood caps are used. This is due to the rubber cap's lower initial modulus of elasticity. For rubber caps, the initial deflection is approximately 0.38 inches; and for Douglas fir caps, this initial deflection is 0.24 inches.

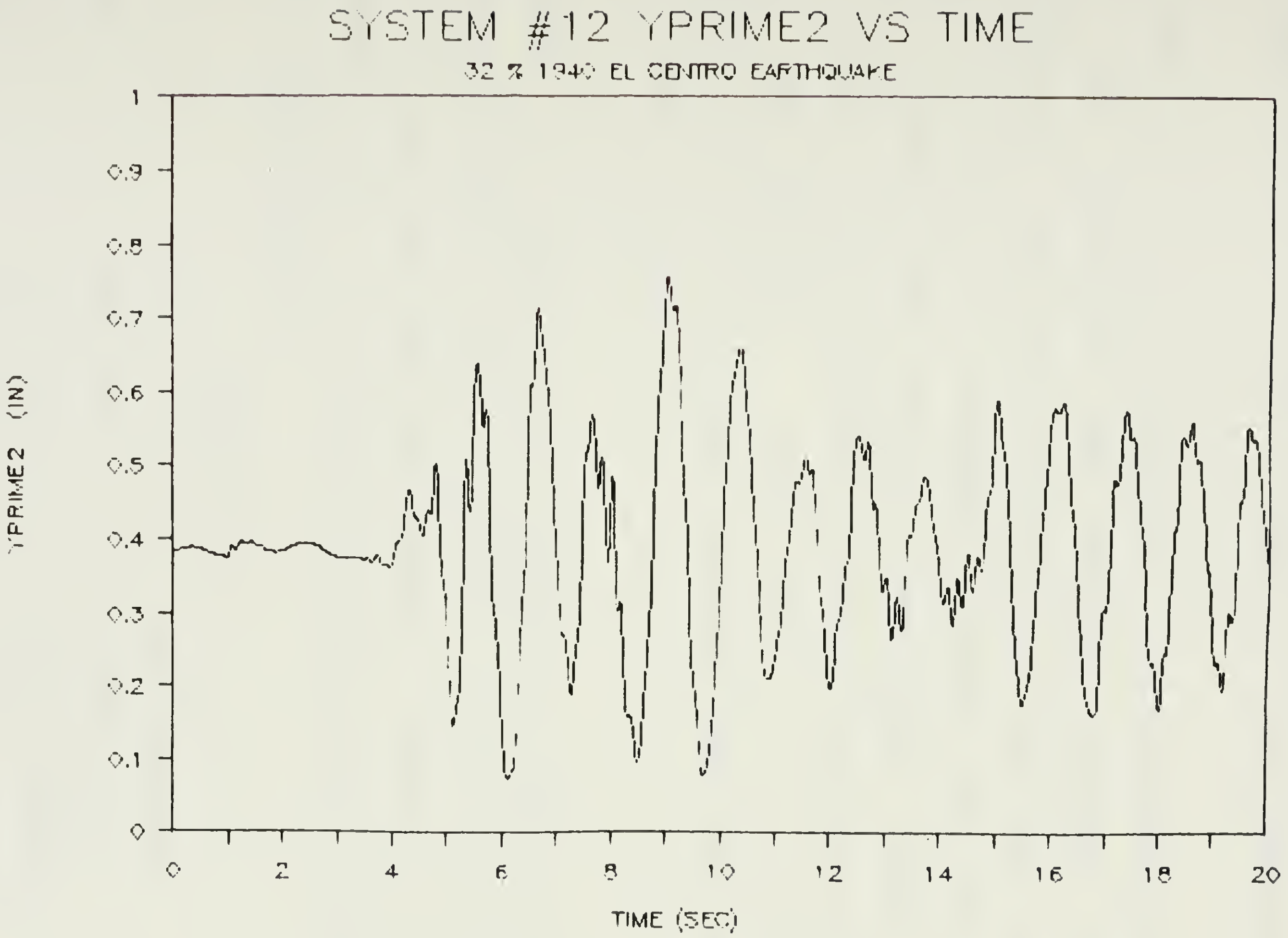

SYSTEM #12 YPRIME2 VS TIME
32 % 1940 EL CENTRO EARTHQUAKE
YPRIME2 (IN)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2
4
6
8
10
12
14
16
18
20
TIME (SEC)

FIGURE 6.7

CHAPTER 7

DYNAMIC ISOLATOR BILINEAR MATERIAL PROPERTY MODEL

7.0 Determination of Dynamic Isolator Blocking Properties

The use of dynamic isolators in drydock blocking systems offer many advantages over standard drydock blocking configurations used today in high seismic risk areas. Dynamic isolators decouple the drydocked submarine from horizontal ground accelerations, dissipate earthquake energy, and significantly reduce accelerations seen by delicate equipment inside the submarine. This chapter will analyze the properties of the D.I.S. dynamic isolator described in section 4.4 and shown in figure (4.7).

Table 7.1 lists dynamic isolator bilinear properties supplied by Dynamic Isolation Systems Incorporated [36] for each side block and keel block isolator. These isolators are of sufficient size and strength to be applicable to submarine drydock blocking system 1.

TABLE 7.1

	SIDE ISOLATOR	KEEL ISOLATOR
QD:	4.55 kips	11.03 kips
KU:	17.8 kips/in	31.31 kips/in
KD:	1.83 kips/in	3.72 kips/in
Kvert:	850 kips/in	1845.83 kips/in

(where Kvert is the vertical stiffness of each isolator)

In order to incorporate these isolator properties into blocking pier stiffness calculations, it is necessary to calculate equivalent elastic moduli for these isolators. Appendix 5 includes the spreadsheets used to perform these calculations. These spreadsheets are virtually the same spreadsheets previously used to calculate blocking pier horizontal stiffness. Four blocking layers are maintained in these spreadsheets. The isolator replaces the oak. It is assumed that the isolator has the same dimensions as the oak layer.

To determine an equivalent modulus of elasticity this new isolator layer is modeled as a cantilever beam/ shear element. To accomplish this, the isolator layer is moved to the top of the four layers of the blocking pier and the other layers are made infinitely stiff. The resulting layer stiffness is made equal to the given value from Table 7.1 by adjusting the value of the isolators' modulus of elasticity. The modulus of rigidity is assumed to be one-tenth of the value of modulus of elasticity. Since the output is a total layer stiffness which includes both bending and shear effects, the exact relationship of modulus of elasticity to modulus of rigidity is not important. Moduli are determined in this manner for side and keel block KU's and KD's.

Once the moduli for the isolators are determined, total blocking pier stiffnesses are determined by using the stiffness spreadsheets as before. Portions of these spreadsheets listing the blocking pier stiffness results are included in Appendix 5. Figures (7.1) and (7.2) are the idealized stress/strain curves for side block and keel isolators respectively subject to horizontal load. The isolators' equivalent modulus values (E1 and E2) shown are those obtained from the spreadsheets. The stress at which the curves change slope (σ_{max}) is obtained from the following equations.

$$\sigma_{max} = P_{max}/A_{top} = XEL*KU/A_{top} \tag{7.1}$$

$$XEL = QD/(KU - KD) \tag{7.2}$$

where:

P_{max} is the maximum force the isolator can withstand without changing the modulus of elasticity.

A_{top} is the top cross-sectional area of the isolator.

7.1 Keel Blocking System Dynamic Isolator Bilinear Model

As can be seen in figure (7.1) and (7.2) a D.I.S. dynamic isolator exhibits bilinear material properties. Therefore, these isolators can be described using a bilinear model similar to that used for wood.

IDEALIZED STRESS/STRAIN CURVE
D.I.S. ISOLATOR
SIDE BLOCK HORIZONTAL LOADING

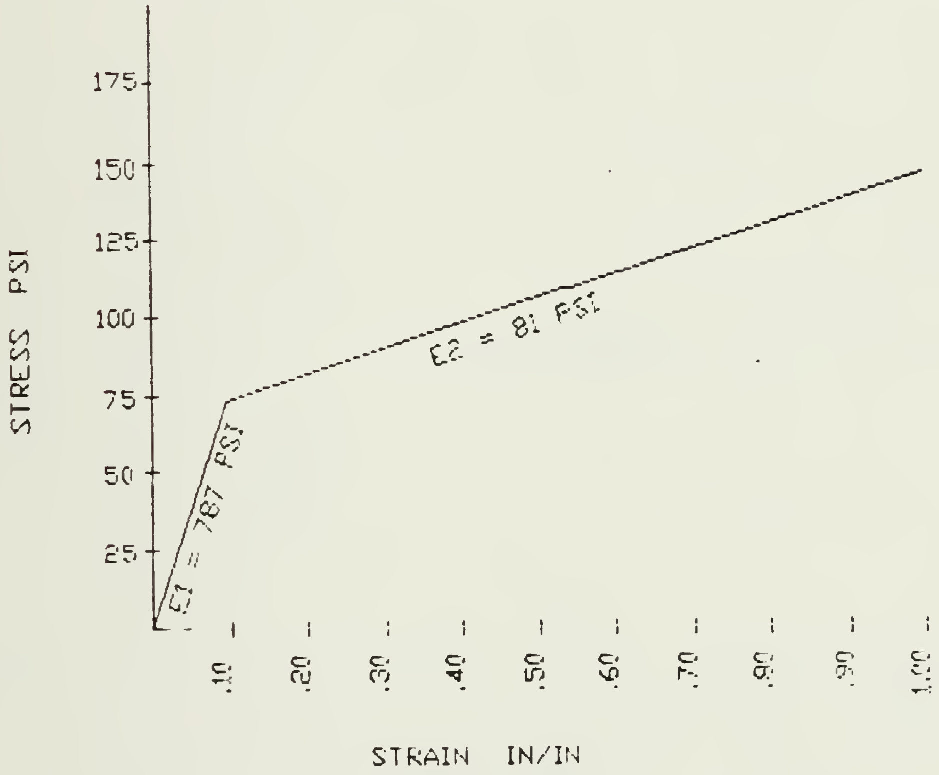


FIGURE 7.1

IDEALIZED STRESS/STRAIN CURVE
D.I.S. ISOLATOR
KEEL BLOCK HORIZONTAL LOADING

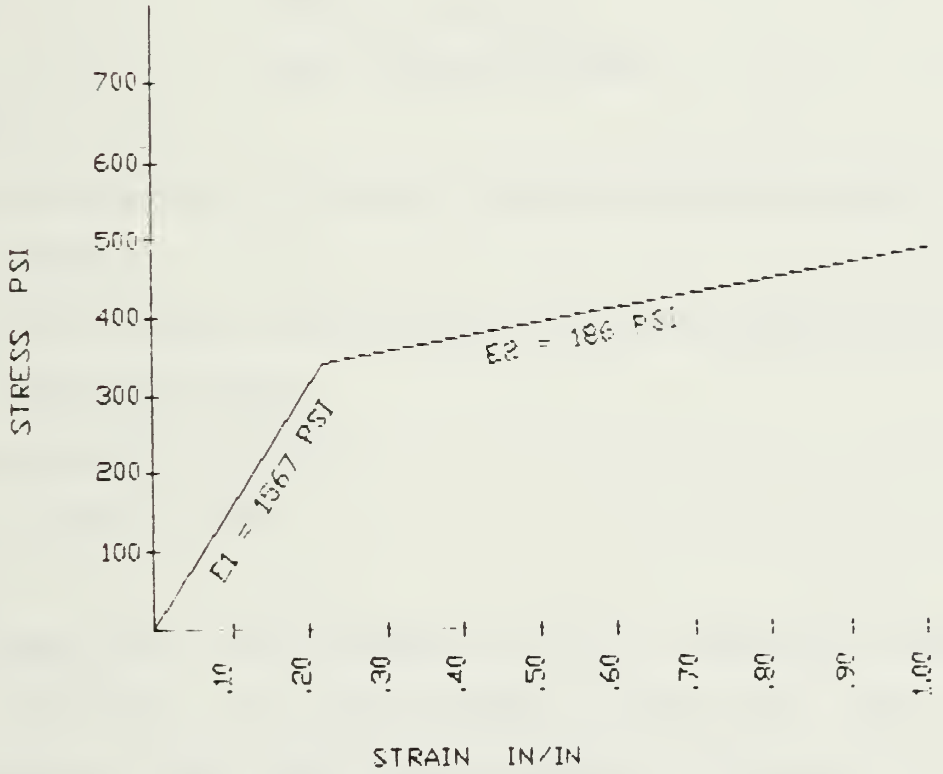


FIGURE 7.2

Figure (5.4), the bilinear force-displacement curve for the horizontal keel blocking system, is a description of the behavior of the D.I.S. dynamic isolator.

The QD value in figure (5.4) for the keel block system (which includes isolators) is obtained using the following equations:

$$XEL1 = P_{max}/KU1 \qquad (7.3)$$

$$QD1 = XEL1*(KU1-KD1) \qquad (7.4)$$

where:

XEL1 is the elastic limit for the keel blocking system in inches.

QD1 is R intercept of the second stiffness slope for the keel blocking system.

KU1 is equal to the khk.

KD1 is equal to khkp.

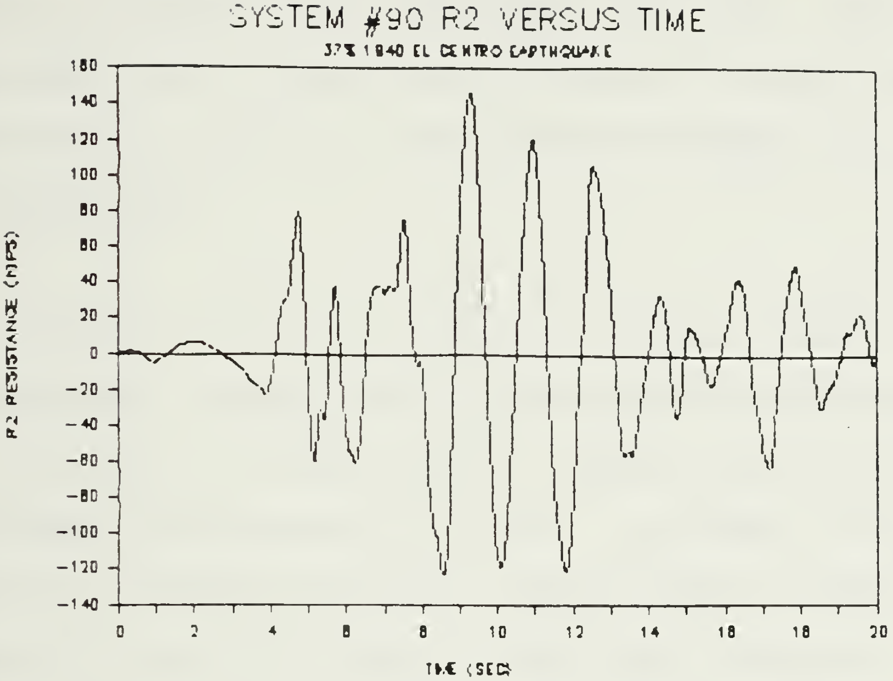
Equations (5.3) through (5.7) in section 5.1 describing the features of the bilinear loop are also directly applicable. The side blocking system is modeled in a similar manner. The "BILINALL" subroutine previously described is used to implement the bilinear model for D.I.S. isolators in the "3DOFRUB" computer program.

7.2 System 1 D.I.S. Isolator Bilinear Analysis Results

Submarine drydock blocking system 1 is used as the baseline for this analysis. The isolators are added to this system as described in section 7.1. The parameters from this system are input into the "3DOFRUB" computer program. The results of this run and the input data are included in Appendix 5.

Several modifications are made to the input data file. These include making the side block and keel block widths extremely large to simulate their being rigidly attached to the dock floor. This would be required if base isolators are used due to the large horizontal displacements which occur. Also, the coefficient of friction for the block on block surface is increased to a very large number to simulate the rigid attachment of the isolators to the blocking pier and caps. This attachment is essential for proper isolator performance. The percentage of critical damping is increased slightly to a value (8 %) consistent with the use of elastomeric base isolation systems [34].

The system fails at 37 % of the 1940 El Centro earthquake due to side block liftoff. Figure (7.3) shows the horizontal side block restoring force, R2, as a function of time for this system (system 90) and for the original system 1.


SYSTEM #90 R2 VERSUS TIME
37% 1940 EL CENTRO EARTHQUAKE
R2 RESISTANCE (KIPS)
160
140
120
100
80
60
40
20
0
−20
−40
−60
−80
−100
−120
−140
0
2
4
6
8
10
12
14
16
18
20
TIME (SEC)

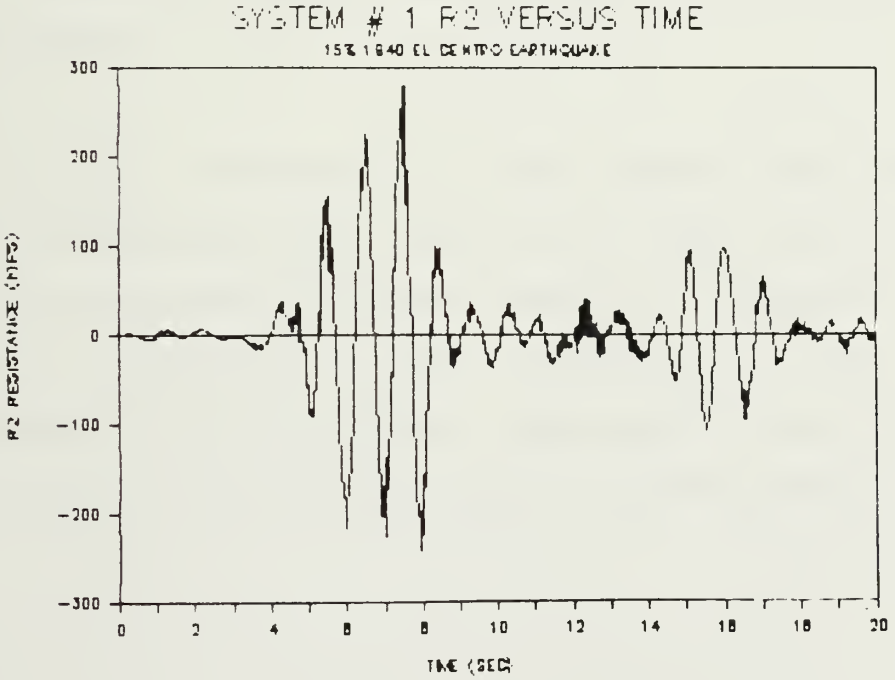

SYSTEM # 1 R2 VERSUS TIME
15% 1940 EL CENTRO EARTHQUAKE
R2 RESISTANCE (KIPS)
300
200
100
0
−100
−200
−300
0
2
4
6
8
10
12
14
16
18
20
TIME (SEC)

FIGURE 7.3

Though system 1 survives less than half the earthquake percentage of system 90, it experiences twice the forces. System 90 also shows smoother and lower frequency force response. This shows how the isolator reduces the forces and accelerations seen by the internal equipment and personnel on the submarine.

Figure (7.4), a plot of force versus horizontal displacement, shows that the side blocks on both systems 1 and 90 behaves in a linear elastic fashion up to their respective earthquake magnitude of failure. As shown by run output in Appendix 5 system 90 fails once bilinear side block system response starts to occur. The large resulting deflections cause the submarine to lift off the side blocks. This shows that these particular isolators are not optimized (tuned) for this system.

Optimal isolators for this system would decrease the modal frequencies until they are no longer efficiently excited by the earthquake frequency spectrum. Presently, system 90's mode 2 frequency (2 HZ) corresponds to the fundamental frequency of the El Centro earthquake. Luchs [21] describes the effect of modal frequencies on system response.

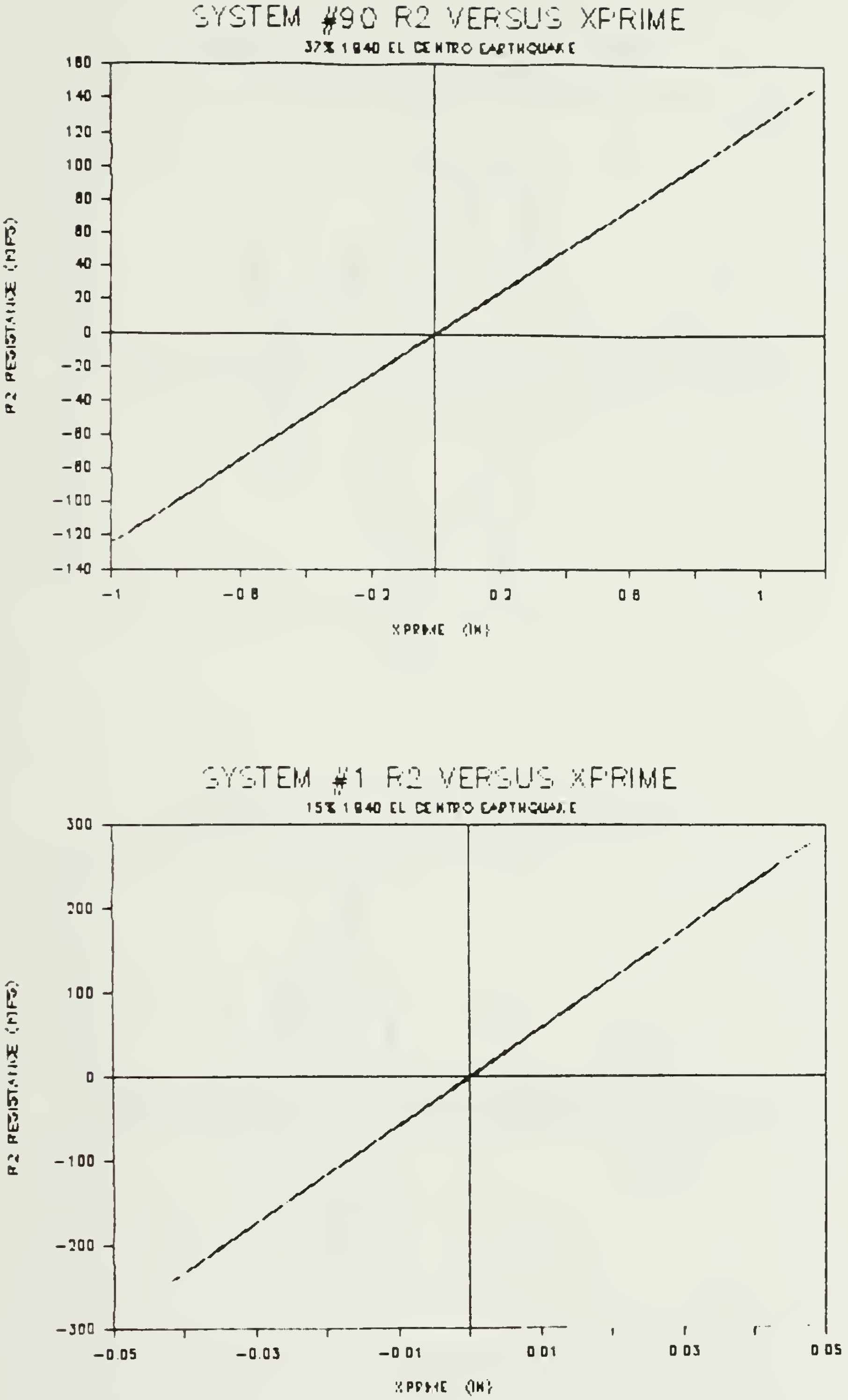

SYSTEM #90 R2 VERSUS XPRIME
37% 1940 EL CENTRO EARTHQUAKE
R2 RESISTANCE (KIPS)
180
140
120
100
80
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-1
-0.6
-0.2
0.2
0.6
1
XPRIME (IN)
SYSTEM #1 R2 VERSUS XPRIME
15% 1940 EL CENTRO EARTHQUAKE
R2 RESISTANCE (KIPS)
300
200
100
0
-100
-200
-300
-0.05
-0.03
-0.01
0.01
0.03
0.05
XPRIME (IN)

FIGURE 7.4

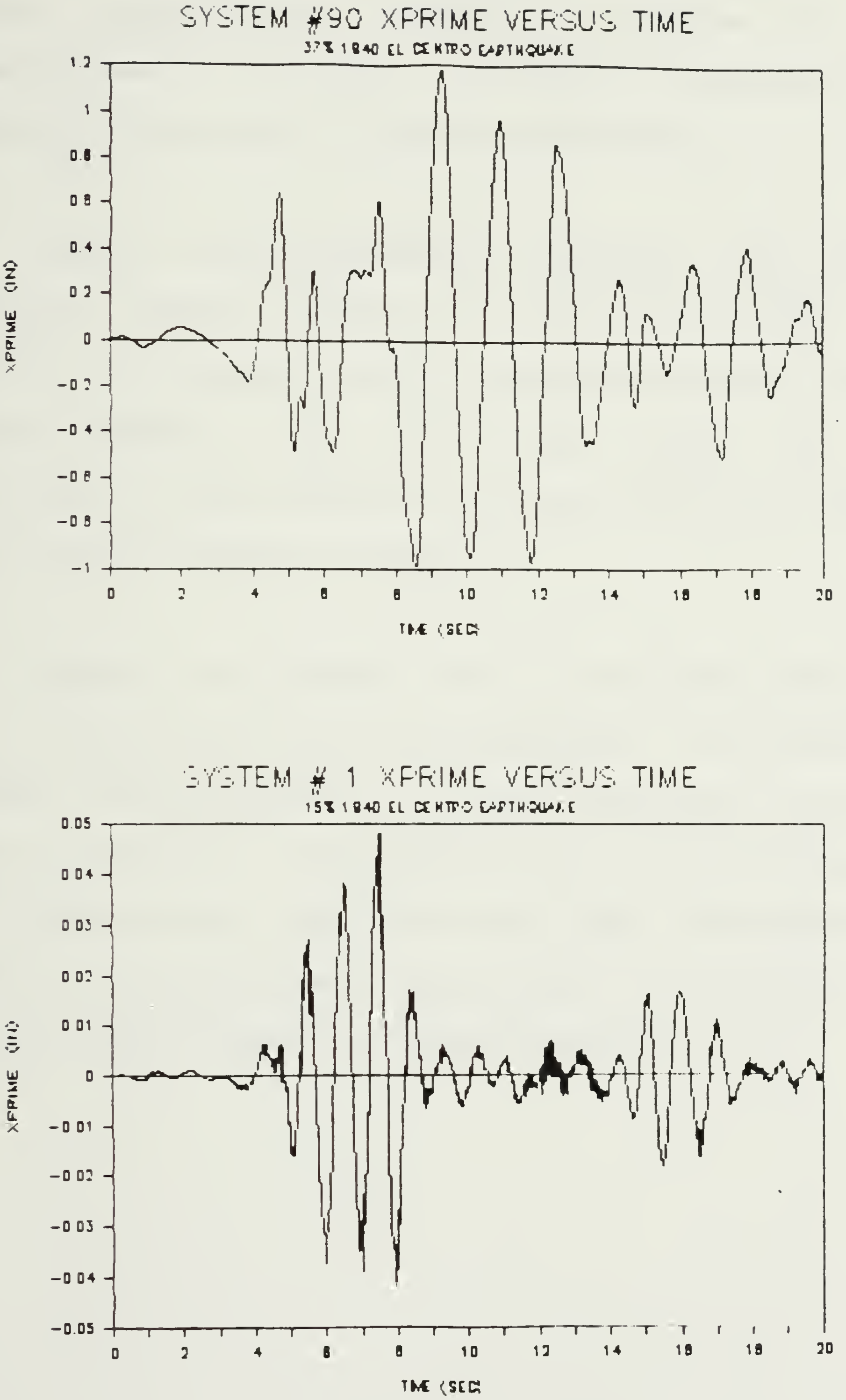

SYSTEM #90 XPRIME VERSUS TIME
37% 1940 EL CENTRO EARTHQUAKE
XPRIME (IN)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
2
4
6
8
10
12
14
16
18
20
TIME (SEC)
SYSTEM # 1 XPRIME VERSUS TIME
15% 1940 EL CENTRO EARTHQUAKE
XPRIME (IN)
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
0
2
4
6
8
10
12
14
16
18
20
TIME (SEC)

FIGURE 7.5

Horizontal displacement versus time is shown in figure (7.5) for the two systems. As expected system 90 shows very large displacements compared to system 1. Horizontal displacements are almost two orders of magnitude greater when isolators are used in this blocking system.

Forces and displacements correlate very strongly with rotation (theta), figure (7.6) for both systems. Again, this shows the dominance of the rotational degree of freedom in these systems. This is a large reason why the use of horizontal base isolation alone may not be the total answer to the lift off failure problem.

Figure (7.7) shows that the isolators have little effect on the vertical system displacements. Both systems 90 and 1 follow the earthquake's vertical excitation very closely in this direction. Displacements would be approximately the same if both systems experienced the same earthquake magnitude. Since the systems are much stiffer in the vertical direction, a much higher response frequency is seen.

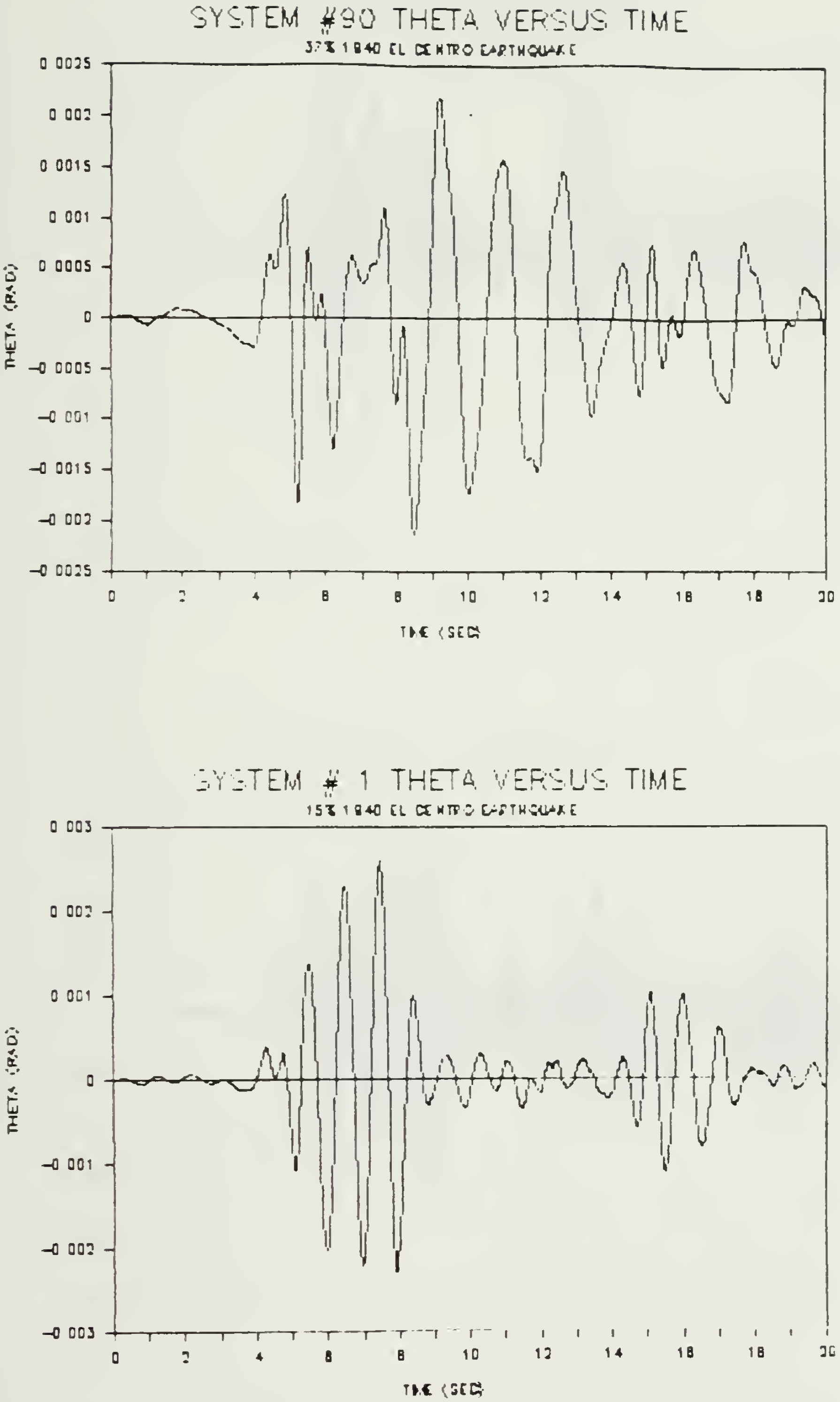
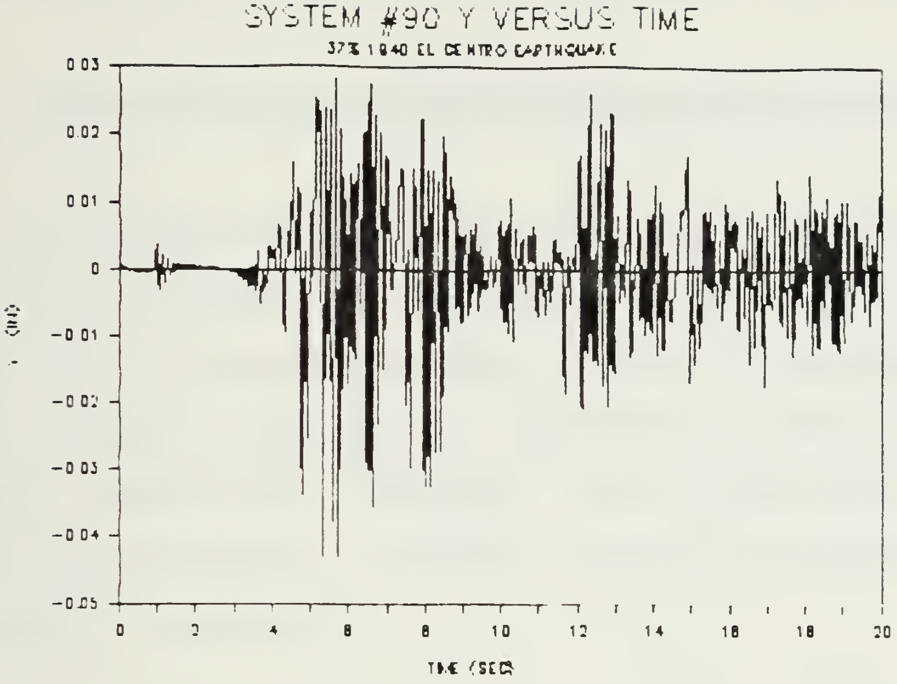

SYSTEM #90 THETA VERSUS TIME
37% 1940 EL CENTRO EARTHQUAKE
THETA (RAD)
0.0025
0.002
0.0015
0.001
0.0005
0
-0.0005
-0.001
-0.0015
-0.002
-0.0025
0
2
4
6
8
10
12
14
16
18
20
TIME (SEC)
SYSTEM # 1 THETA VERSUS TIME
15% 1940 EL CENTRO EARTHQUAKE
THETA (RAD)
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
0
2
4
6
8
10
12
14
16
18
20
TIME (SEC)

FIGURE 7.6


SYSTEM #90 Y VERSUS TIME
37% 1940 EL CENTRO EARTHQUAKE
Y (IN)
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
0
2
4
6
8
10
12
14
16
18
20
TIME (SEC)

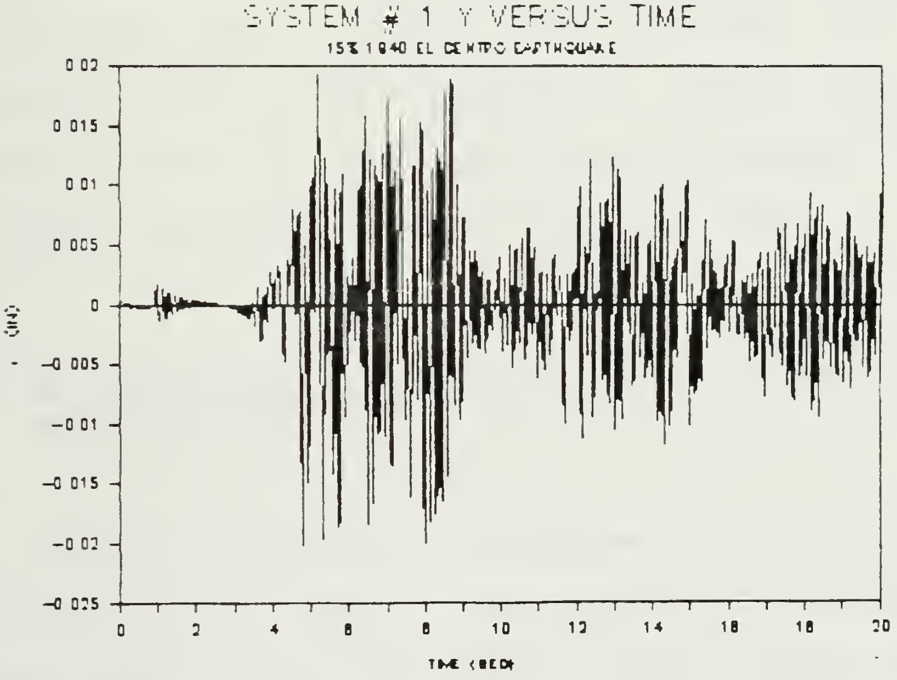

SYSTEM # 1 Y VERSUS TIME
15% 1940 EL CENTRO EARTHQUAKE
Y (IN)
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.025
0
2
4
6
8
10
12
14
16
18
20
TIME (SEC)

FIGURE 7.7

CHAPTER 8

COMPARISON OF SUBMARINE DRYDOCK BLOCKING SYSTEM MATERIALS

8.0 Submarine Drydock Blocking System Material Comparison

The eleven submarine drydock blocking systems previously analyzed by Sigman [16] are reexamined using the bilinear wood model and bilinear rubber model (using 1" rubber caps). Using the procedures described in sections 5.1 and 6.1 for wood and rubber respectively, stiffness and QD values are obtained for the eleven systems. A complete listing of these properties is included in Appendix 4.

These values are input into the "3DOFRUB" computer program for each of the eleven systems while all other submarine and dry dock parameters remain the same. The program is run for each system using the same 1940 El Centro earthquake acceleration time history as Sigman.

8.1 Bilinear Wood Versus Sigman's Drydock Blocking System Material Model

Sigman's results are discussed in section 3.2 and are shown in figure (3.2). The survival percentages for the eleven systems as determined by Sigman ranged from 13 to 39 % (mean 26%) of the 1940 El Centro earthquake acceleration time history (0.06 to 0.18 g's peak).

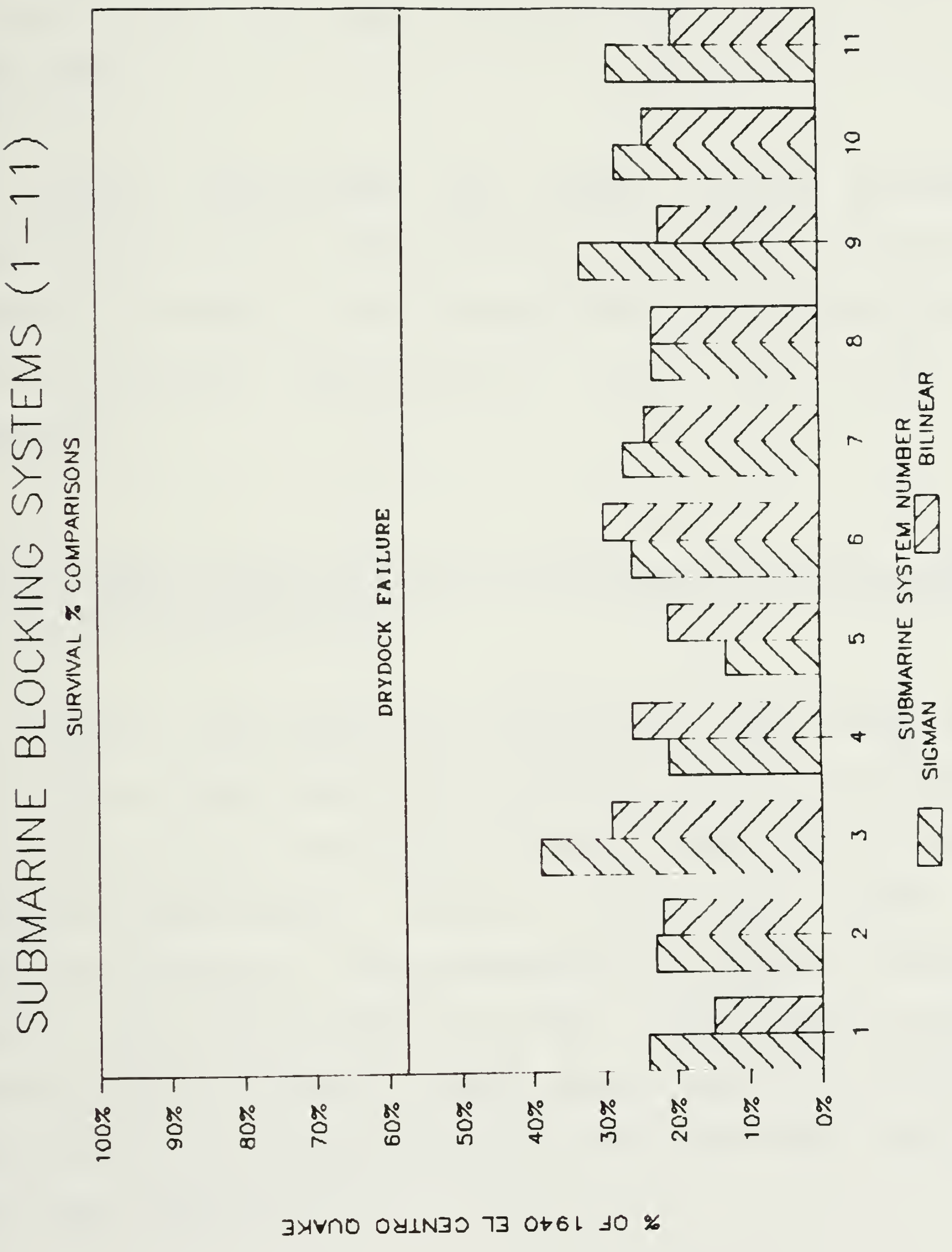

SUBMARINE BLOCKING SYSTEMS (1-11)
SURVIVAL % COMPARISONS
DRYDOCK FAILURE
% OF 1940 EL CENTRO QUAKE
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
1
2
3
4
5
6
7
8
9
10
11
SUBMARINE SYSTEM NUMBER
SIGMAN
BILINEAR

FIGURE 8.1

Figure (8.1) compares the bilinear wood model results with Sigman's.Survival percentages range from 15 to 30 % (mean 23 %) and in "g's" the range is 0.07 to 0.14 g's for the bilinear wood model.

Overall the bilinear wood model predicts failures at approximately 10 % lower acceleration values. In the case of systems 9 through 11 the bilinear wood model predicts failures at accelerations approximately 30 % lower than Sigman predicted.

8.2 Bilinear Rubber Versus Bilinear Wood Drydock Blocking System Material Model

Figure (8.2) compares the bilinear rubber model results with the bilinear wood model. Survival percentages range from 24 to 42 % (0.11 to 0.19 g's) with a mean of 30 % for the bilinear rubber model. Overall the bilinear rubber model predicts survival at approximately 30 % higher acceleration values than the bilinear wood model. In the case of systems 1 through 5 the bilinear rubber model predicts survival at accelerations approximately 50 % higher than what the bilinear wood model predicts.

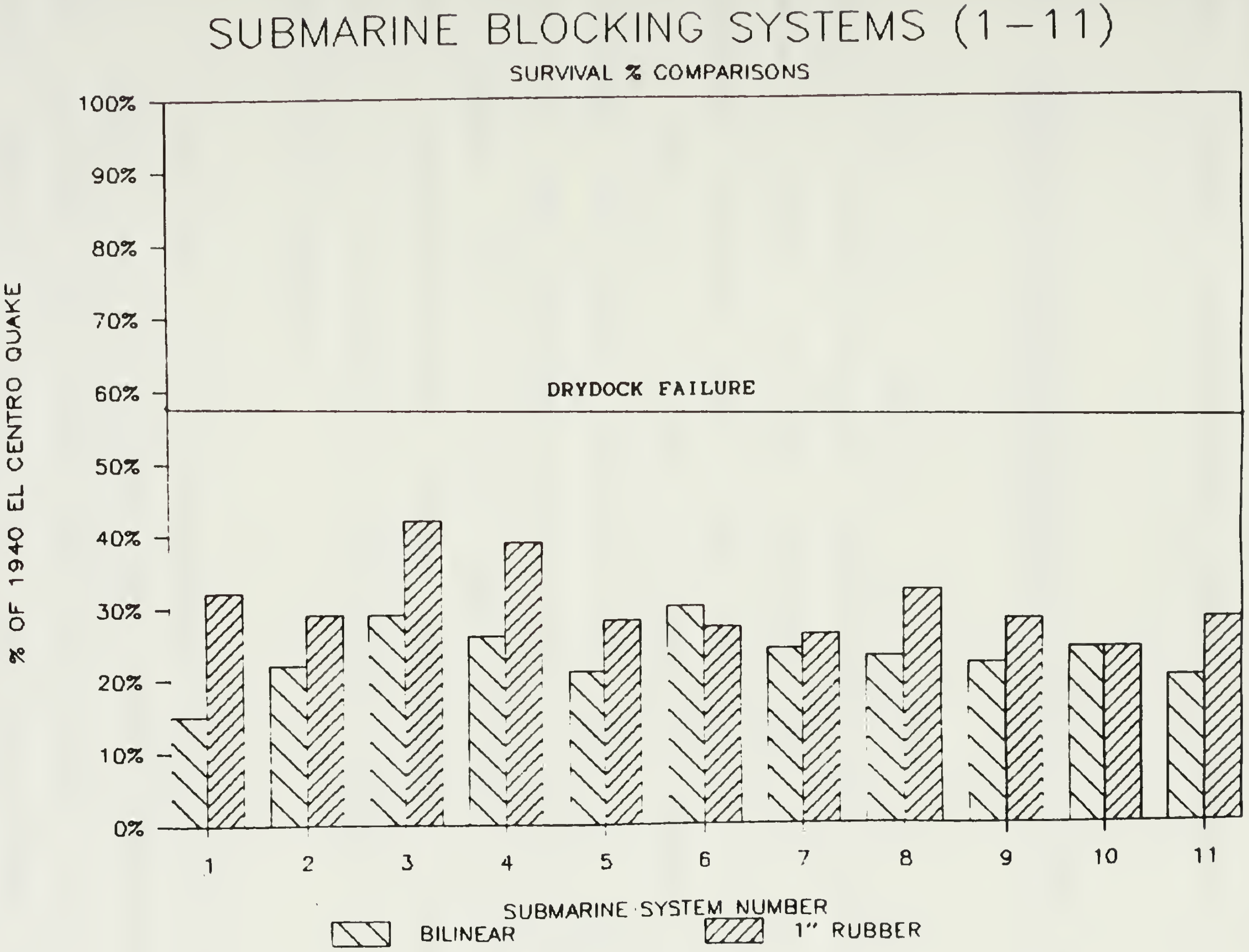

SUBMARINE BLOCKING SYSTEMS (1-11)
SURVIVAL % COMPARISONS
% OF 1940 EL CENTRO QUAKE
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
DRYDOCK FAILURE
1
2
3
4
5
6
7
8
9
10
11
SUBMARINE SYSTEM NUMBER
BILINEAR
1" RUBBER

FIGURE 8.2

In one case, system 6, the bilinear rubber model predicts slightly lower survivability than the bilinear wood model. However, in every other case the bilinear rubber model predicts equal to significantly greater survivability.

8.3 Overall Comparison Among Bilinear Wood, Bilinear Rubber, Isolators, and Sigman Results.

Figure (8.3) combines the results for the eleven submarine drydock blocking systems using the various blocking material models. In every material model for all eleven systems failure is due to side block liftoff. Roughly, this figure shows that the use of rubber as a capping material increases the systems' survivability, and the use of the bilinear model decreases the survivability from the model used by Sigman. This is not always the case possibly due to system modal frequency effects. Since the behavior of system 1 is typical of the behavior of all eleven systems, it is chosen for further analysis.

Figure (8.4) is the comparison of the survival percentage of system 1 using the Sigman's model, the bilinear wood model, the bilinear rubber model, and the bilinear D.I.S. isolator model described in chapter 7. This figure clearly indicates the potential use of rubber caps and/or dynamic isolators in improving submarine drydock blocking system survivability.

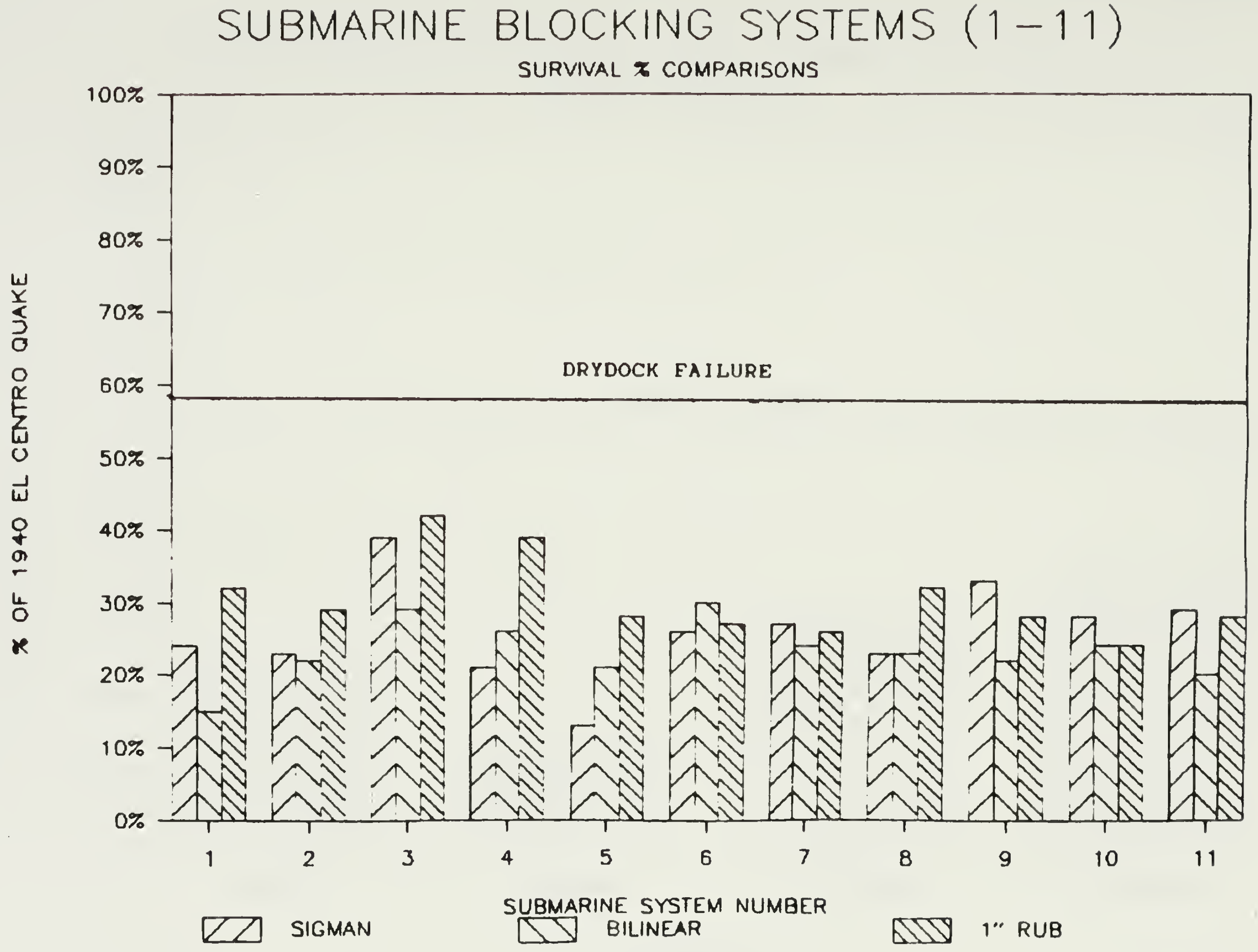

SUBMARINE BLOCKING SYSTEMS (1–11)
SURVIVAL % COMPARISONS
% OF 1940 EL CENTRO QUAKE
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
DRYDOCK FAILURE
1
2
3
4
5
6
7
8
9
10
11
SUBMARINE SYSTEM NUMBER
SIGMAN
BILINEAR
1" RUB

FIGURE 8.3

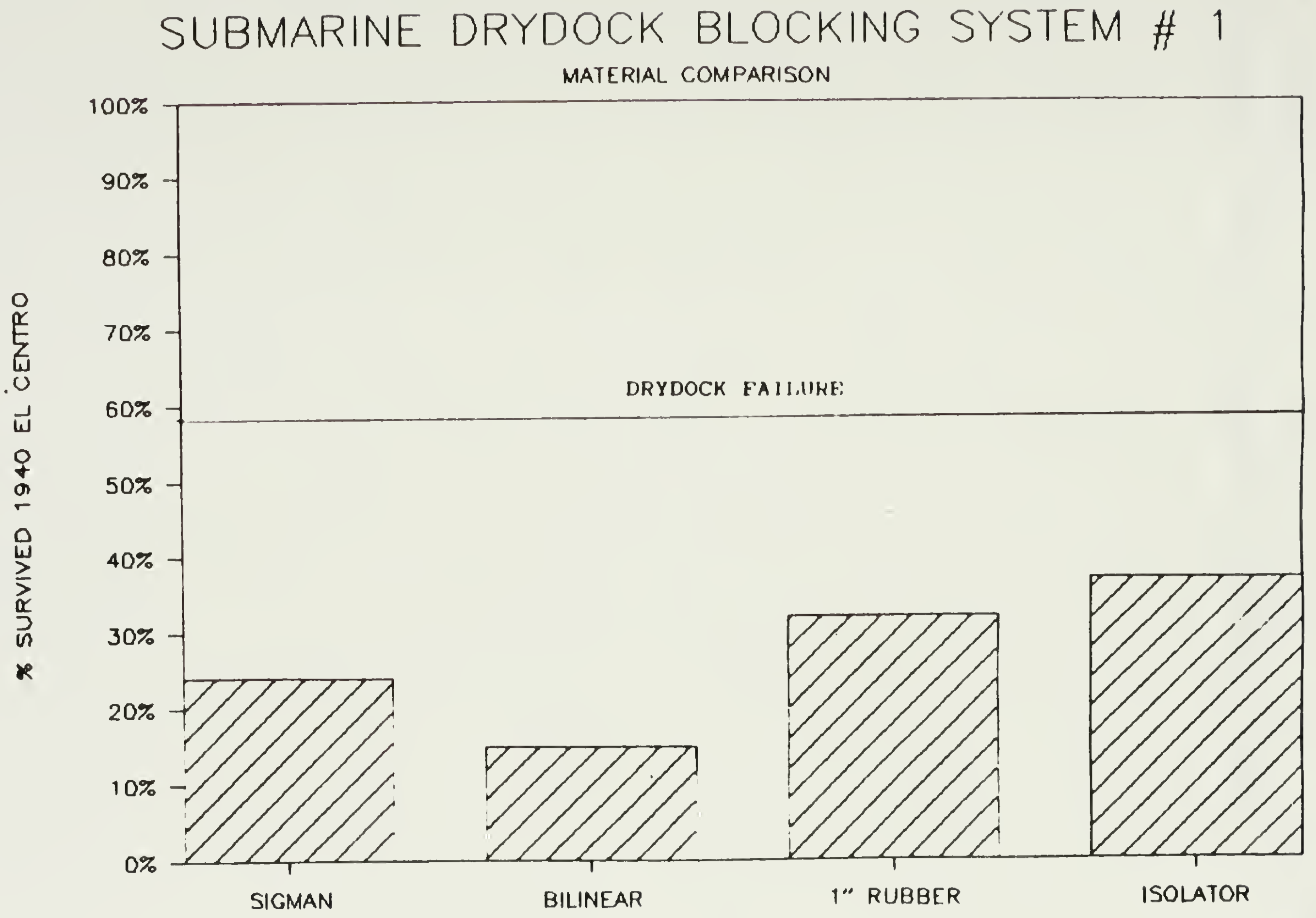

SUBMARINE DRYDOCK BLOCKING SYSTEM # 1
MATERIAL COMPARISON
% SURVIVED 1940 EL CENTRO
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
DRYDOCK FAILURE
SIGMAN
BILINEAR
1" RUBBER
ISOLATOR

FIGURE 8.4

The baseline condition in this thesis is considered to be the bilinear wood model. This best describes the condition of the submarine drydock blocking systems today. Compared to this baseline, the rubber caps and isolators each approximately double the system's survivability.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

9.0 Conclusions

U.S. Naval shipyards where submarines are drydocked are located in regions of the United States where significant earthquakes are known to occur. The graving dry docks at these shipyards are currently designed to withstand earthquake accelerations up to 0.26 g's. Previous research using linear elastic material models showed that submarine drydock blocking systems would fail due to side block liftoff at accelerations significantly lower than the 0.2 g level required by current Navy drydocking standards.

This thesis confirms these results using a material model for wood which more closely represents its actual behavior. Using this bilinear model, it is determined that the submarine drydock blocking systems would fail by side block liftoff at even lower accelerations due to plastic deformation of the Douglas fir capping material.

New materials are then analyzed in order to determine their potential for increasing system survivability. The materials analyzed are natural rubber and dynamic isolators. The rubber is used as a substitute for the Douglas fir soft

cap, and the dynamic isolators are used as a substitute for the oak (hard wood) layer of the blocking systems.

The response behavior of rubber and the dynamic isolators also allows them to be modeled as bilinear materials. It is determined that significant increases in survivability occur when these materials are incorporated in the blocking systems. Rubber caps and isolators either singly or in combination are very attractive potential solutions to the submarine drydock blocking systems' survivability problem.

Figures (8.3) and (8.4) show that all the systems examined in this thesis, including the systems where rubber caps or isolators are used, fail well before the dry dock itself fails (0.26 g's). They also fail well below the required 0.2 g level. It is clear that the current submarine drydock blocking systems provide inadequate protection of the submarines from accelerations caused by earthquakes that will probably be experienced in the near future.

9.1 Recommendations

Since the survivability of submarine drydock blocking systems is essential at least up to the point where the dry dock itself survives, a new blocking system for these submarines needs to be designed. The "3DOFRUB" computer

program with the bilinear models included should be used as a design tool in this effort.

In order to improve the design of the current blocking systems the following studies are recommended. First, determine the effect of side block cap angle, side block buildup height, and block on hull friction coefficients. Second, determine the effect of adding additional restraints to the submarine blocking system including the use of wale shores. Third, determine the effect of tuning dynamic isolators to enhance their performance. The use of rubber as a substitute capping material needs to be further analyzed including varying the thickness of the cap. Finally, combinations of use of isolators and rubber caps need to be studied.

Other design features need to be examined including increasing blocking stiffness, widening or restraining the keel and side blocks to prevent overturning, and changing the drydock blocking system modal frequencies. In addition, a study needs to be done examining the effects of using earthquake acceleration time histories representative of particular dry dock locations. If possible, experimental studies should be done to determine the validity of the "3DOFRUB" computer program and the bilinear subroutines.

Additional studies need to be done on the material properties of rubber, particularly the variation of shear modulus when subject to compressive loads. Even further studies need to be done on existing wood materials used in drydock blocks. These tests should include determining the modulus of elasticity of Douglas fir and oak when they are loaded at various grain angles. Biaxial loading should also be studied.

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APPENDIX 1

1. "3DOFRUB" Computer Program Listing
2. "BILINALL" and "RUBBER" Subroutine Listings
3. Sample Input Data File and Output File

```

$title:  '3DOFRUB'
$nofloatcalls
$storage: 2

C-----------------------------------------------------------------

C     NON-LINEAR THREE DEGREE OF FREEDOM SYSTEM RESPONSE
C      USING FOURTH ORDER RUNGE-KUTTA METHOD
C      AND BILINEAR VERTICAL & HORIZONTAL STIFFNESSES
C        WITH HORZ/VERT ACCELERATION INPUT
C        AND DISPLACEMENT OUTPUT FILES
C      (INCLUDES WALE SHORE EFFECTS & HIGH BUILDUPS
C      AND THE USE OF RUBBER CAPS)

C-----------------------------------------------------------------


      integer NN,l,mm,n,hull,nsys,flag10,ll
        integer flag1,flag2,flag3,flag4,flag5,flag6,flag7,flag8
      integer KY1,KY2,KY3,KY4,WWW1,YYY1,UUU1,WWW2,YYY2,UUU2,WWW3,YYY3
      integer UUU3,WWW4,YYY4,UUU4,UUU5,WWW5,YYY5,decrr
      real*8 beta,weight,h,Ik,gravity,AAA,Ks,sidearea,keelarea,plside
      real ac(2002),acv(2002),xx(2002),yy(2002),tt(2002),rrr(2002)
      real*8 m(4,4),cx(4,4),k(4,4),ko(4,4),crit2,crit3
        real*8 baseside,basekeel,htside,htkeel
        real*8 dtau,maxx,maxt,maxy,timex,timet
        real*8 rf1,rf2,rf3,hf1,hf2,hf3,ampacc,mass,ampacmax
        real*8 kvs,kvk,kvkp,khs,khk,kshp,kkhp,kvsp,base,counter,time
        real*8 time1,time2,time3,time4,time5,time6,time7,time8
      real*8 x,t,y,xold,told,yold,XSCL(6)
      real*8 bbb,ccc,w12,w1,w22,w2,w32,w3,mode1,mode3
      real*8 mmx1,mmang1,mmx3,mmang3,crit4,alpha,LLL
        real*8 timey,mmmmm1,mmmmm2,mmmmm3,mmmmm4
      real*8 R,S,TAU,A(6),B(6),C(6),D(6),E(6),F(6),G(6),HH(6)
      real*8 br,amp,plkeel,u1,u2,XPRIM,VEL
      real*8 KU1,KD1,khkb,QD1,XEL1,XMAX1,XMIN1,RR1,ZZ1,WZ1,VEL1
      real*8 KU2,KD2,khsb,QD2,XEL2,XMAX2,XMIN2,RR2,ZZ2,WZ2,YPRIM1
      real*8 KU3,KD3,kvsb1,QD3,YEL1,YMAX1,YMIN1,RR3,ZZ3,WZ3,DELTA
      real*8 KU4,KD4,kvsb2,YEL2,YMAX2,YMIN2,RR4,ZZ4,WZ4,YPRIM2,VEL2
      real*8 KU5,KD5,kvkb,QD4,YEL3,YMAX3,YMIN3,RR5,ZZ5,WZ5,YPRIM3
      CHARACTER*40 DEC,DECV,quakname,hname,vname
      character*40 sbfname,aclfname,outfname,vfname



C     READ IN VESSEL AND DRYDOCK DATA; VESSEL WEIGHT,KG,I(ABOUT KEEL),
C     TIME INCREMENT OF DATA POINTS,VERTICAL STIFFNESS OF SIDE AND
C     KEEL PIERS,HORIZONTAL STIFFNESS OF SIDE AND KEEL PIERS,
C     GAVITATIONAL CONSTANT,SIDE BLOCK BASE AND HEIGHT,
C     KEEL BLOCK BASE AND HEIGHT,
C     BLOCK-BLOCK AND BLOCK-HULL FRICTION COEFFICIENTS,
C     SIDE AND KEEL BLOCK'S PROPORTIONAL LIMIT,
C     SIDE PIER-VESSEL CONTACT AREA,KEEL PIER-VESSEL CONTACT AREA,
C     CAP BLOCK INCLINATION ANGLE.

C       OPEN INPUT FILES AND READ DATA

        write(*,'(a)') ' ENTER SHIP/BUILDUP FILE NAME ... '
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          read(*,'(a)') sbfname

          open(4,file= sbfname,status='old',form='formatted')

          read(4,*) weight,h,Ik,kvs,kvsp,kvk,AAA,Ks
        read(4,*) khs khk,kshp,kkhp,QD1,QD2,QD3,gravity
          read(4,*) baseside, basekeel,htside,htkeel,u1,u2
          read(4,*) br,plside,plkeel,sidearea,keelarea,zeta
        read(4,*) hull,nsys,beta,QD4,kvkp
        CLOSE (4)

        write (*,*) 'DO YOU WANT RESPONSE OUTPUT FILES? (Y OR N)'
        read(*,'(a)') dec
        if (dec.eq.'Y'.or.dec.eq.'y') then
        write(*,*) 'INPUT DESIRED RESISTANCE OUTPUT: (1,2,3,4,5)'
        write(*,*) 'KEEL HORIZONTAL FORCE       = 1'
        write(*,*) 'SIDE BLOCK HORIZONTAL FORCE = 2'
        write(*,*) 'LEFT SIDE BLOCK VERT FORCE  = 3'
        write(*,*) 'RIGHT SIDE BLOCK VERT FORCE = 4'
        write(*,*) 'KEEL BLOCK VERTICAL FORCE   = 5'
        read(*,*) decrr
        endif

        do 12,i=1,3
1       do 13,j=1,3
2       m(i,j)=0.0
2       k(i,j)=0.0
2       cx(i,j)=0.0
2       ko(i,j)=0.0
2   13  continue
1   12  continue


    C   CALCULATE SYSTEM PARAMETERS

        mass=weight/gravity
        LLL=sqrt((htside-htkeel)**2D0+(br/2D0)**2D0)
        alpha=asin((htside-htkeel)/LLL)

        m(1,1)=mass
        m(1,3)=h*mass
        m(2,2)=mass
        m(3,1)=mass*h
        m(3,3)=Ik

        k(1,1)=(2D0*Ks+2D0*khs+khk)
        k(1,3)=(2D0*Ks*AAA+2D0*khs*LLL*sin(alpha))
        k(3,1)=k(1,3)
        k(2,2)=(2D0*kvs+kvk)
        k(3,3)=(2D0*Ks*AAA**2D0+2D0*khs*((LLL*sin(alpha))**2D0)+
       + (2D0*kvs*((LLL*cos(alpha))**2D0)-(weight*h)))
        ko(1,1)=k(1,1)
        ko(1,3)=k(1,3)
        ko(3,1)=k(3,1)
        ko(2,2)=k(2,2)
        ko(3,3)=k(3,3)

    C   DETERMINE NATURAL FREQUENCIES OF SYSTEM
        bbb=-(m(1,1)*k(3,3)+m(3,3)*k(1,1)-m(1,3)*k(3,1)-m(3,1)*k(1,3))
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     + /(m(1,1)*m(3,3)-m(1,3)*m(3,1))
      ccc=(k(1,1)*k(3,3)-k(1,3)*k(3,1))/(m(1,1)*m(3,3)-m(1,3)*m(3,1))
C

C     NATURAL FREQ. MODE #1

      w12=(-bbb-sqrt(bbb**2-4D0*ccc))/2D0
      w1=sqrt(w12)

C     NATURAL FREQ. MODE #2

         w22=k(2,2)/m(2,2)
      w2=sqrt(w22)
C     NATURAL FREQ. MODE #3

         w32=(-bbb+sqrt(bbb**2-4D0*ccc))/2D0
      w3=sqrt(w32)

C     MODE SHAPE #1 & #3

      mode1=(m(1,3)*w12-k(1,3))/(-m(1,1)*w12+k(1,1))
      mode3=(m(1,3)*w32-k(1,3))/(-m(1,1)*w32+k(1,1))
C     DETERMINE C11,C13,C31,C33
      mmx1=m(1,1)+m(1,3)/mode1
      mmang1=mode1*m(3,1)+m(3,3)
      mmx3=m(1,1)+m(1,3)/mode3
      mmang3=mode3*m(3,1)+m(3,3)
      mmmmm1=2D0*zeta*mmx1*w1
      mmmmm2=2D0*zeta*mmx3*w3
      mmmmm3=2D0*zeta*mmang1*w1
      mmmmm4=2D0*zeta*mmang3*w3





      cx(1,3)=(mmmmm1-mmmmm2)/(1/mode1-1/mode3)
      cx(1,1)=mmmmm1-(cx(1,3)/mode1)
      cx(2,2)=2D0*zeta*m(2,2)*w2
      cx(3,1)=(mmmmm3-mmmmm4)/(mode1-mode3)
      cx(3,3)=mmmmm3-(cx(3,1)*mode1)


C     READ IN ACCELERATION DATA

      CALL ACCLINPT(amp,ac,acv,dtau,quakname,hname,vname)

C     ESTABLISH FAILURE CRITERIA AND FLAGS

      crit2=min (u1,u2)
      crit3= (6.6D-1*baseside-1.2D1)/htside
      crit4=basekeel/(6D0*htkeel)
      ampacc=1D0
      counter=0.0
      ampacmax=0.0
10000 continue
        write(*,*) ampacc
      flag1=0
      flag2=0
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      flag3=0
      flag4=0
      flag5=0
      flag6=0
      flag7=0
      flag8=0
      flag10=0
      maxx=0.0
      maxt=0.0
      maxy=0.0
      mm=0
      x=0.0
      y=0.0
      t=0.0
      xold=0.0
      yold=0.0
      told=0.0
      R=0.0
      S=0.0
      TAU=0.0

C     INITIALIZING BILINEAR VARIABLES

C     INITIALIZING DELTA

      if (kvs.eq.kvsp) then
        YEL1=0.0
        elseif (kvs.ne.kvsp) then
        YEL1=QD3/(kvs-kvsp)
      endif
      if (kvk.eq.kvkp) then
        YEL3=0.0
        elseif (kvk.ne.kvkp) then
        YEL3=QD4/(kvk-kvkp)
      endif
      DELTA=weight/(2D0*kvs+kvk)
      if (QD3.ge.0.0.or.QD4.ge.0.0) then
        kvsb1=kvs
        kvkb=kvk
      goto 100
      endif
      if (DELTA.lt.YEL3.and.DELTA.lt.YEL1) then
        kvsb1=kvs
        kvkb=kvk
      elseif (DELTA.ge.YEL3.or.DELTA.ge.YEL1) then
        kvsb1=kvsp
        kvkb=kvkp
        DELTA=YEL3+(weight-(YEL3*(2D0*kvs+kvk)))/(2D0*kvsp+kvkp)
      endif

100   continue

C     INITIALIZING KEEL HORIZONTAL STIFFNESS

      KU1=khk
      KD1=kkhp
      khkb=KU1
      if (QD1 .eq. 0.0) goto 101
      KY1=0
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```
      XEL1=QD1/(KU1-KD1)
      XMAX1=0.0
      XMIN1=0.0
      RR1=0.0
      ZZ1=0.0
      WZ1=0.0
      WWW1=0.0
      YYY1=0.0
      UUU1=0.0

101   continue

C     INITIALIZING SIDE BLOCK HORIZONTAL STIFFNESS

      KU2=khs
      KD2=kshp
      khsb=KU2
      if (QD2 .eq. 0.0) goto 102
      KY2=0
      XEL2=QD2/(KU2-KD2)
      XMAX2=0.0
      XMIN2=0.0
      RR2=0.0
      ZZ2=0.0
      WZ2=0.0
      WWW2=0.0
      YYY2=0.0
      UUU2=0.0

102   continue

C     INITIALIZING LEFT SIDE BLOCK VERTICAL STIFFNESS

      KU3=kvs
      KD3=kvsp
      if (QD3 .eq. 0.0) goto 103
      KY3=0
      YMAX1=0.0
      YMIN1=0.0
      RR3=kvsb1*DELTA
      ZZ3=0.0
      WZ3=0.0
      WWW3=0.0
      YYY3=0.0
      UUU3=0.0

103   continue

C     INITIALIZING RIGHT SIDE BLOCK VERTICAL STIFFNESS
      KU4=kvs
      KD4=kvsp
      kvsb2=kvsb1
      if (QD3 .eq. 0.0) goto 104
      KY4=0
      YEL2=YEL1
      YMAX2=0.0
      YMIN2=0.0
      RR4=kvsb2*DELTA
      ZZ4=0.0
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```
      WZ4=0.0
      WWW4=0.0
      YYY4=0.0
      UUU4=0.0

104   continue

C     INITIALIZING KEEL VERTICAL STIFFNESS

      KU5=kvk
      KD5=kvkp
      if (QD4.eq.0.0) goto 105
      KY5=0
      YMAX3=0.0
      YMIN3=0.0
      RR5=kvkb*DELTA
      ZZ5=0.0
      WZ5=0.0
      WWW5=0.0
      YYY5=0.0
      UUU5=0.0

105   continue

C     IMPLEMENTATION OF EQUATIONS OF MOTION INTO THE
C      RUNGE-KUTTA FORMULUS

      do 301.1=1,2000

C     CALCULATE BILINEAR STIFFNESS AND RESISTANCE

C     CALCULATE KEEL HORIZONTAL BILINEAR STIFFNESS

      if (QD1 .eq. 0.0) goto 106

      CALL BILINALL(x,S,khkb,RR1,KD1,QD1,KU1,XEL1,XMAX1,XMIN1,
     +  KY1,ZZ1,WZ1,WWW1,YYY1,UUU1)

106   continue

C     CALCULATE SIDE BLOCK HORIZONTAL BILINEAR STIFFNESS

      XPRIM=+x+LLL*t*sin(alpha)

      if (QD2 .eq. 0.0) goto 107

      VEL=+S+LLL*TAU*sin(alpha)

      CALL BILINALL(XPRIM,VEL,khsb,RR2,KD2,QD2,KU2,XEL2,XMAX2,XMIN2,
     +  KY2,ZZ2,WZ2,WWW2,YYY2,UUU2)

107   continue

C     CALCULATE LEFT SIDE BLOCK VERTICAL BILINEAR STIFFNESS

      YPRIM1=-y-t*LLL*cos(alpha)+DELTA

      if (QD3 .eq. 0.0) goto 108
      if (QD3 .gt. 0.0) then
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```

      VEL1=-R-TAU*LLL*cos(alpha)

      CALL BILINALL(YPRIM1,VEL1,kvsb1,RR3,KD3,QD3,KU3,YEL1,YMAX1,
     +  YMIN1,KY3,ZZ3,WZ3,WWW3,YYY3,UUU3)

      elseif (QD3 .lt. 0.0) then

      CALL RUBBER(YPRIM1,kvsb1,RR3,KD3,QD3,KU3,YEL1)

      endif

108   continue

C     CALCULATE RIGHT SIDE BLOCK VERTICAL BILINEAR STIFFNESS

      YPRIM2=-y+t*LLL*cos(alpha)+DELTA

      if (QD3 .eq. 0.0) goto 109
      if (QD3 .gt. 0.0) then

      VEL2=-R+TAU*LLL*cos(alpha)

      CALL BILINALL(YPRIM2,VEL2,kvsb2,RR4,KD4,QD3,KU4,YEL2,YMAX2,
     +  YMIN2,KY4,ZZ4,WZ4,WWW4,YYY4,UUU4)

      elseif (QD3 .lt. 0.0) then

      CALL RUBBER(YPRIM2,kvsb2,RR4,KD4,QD3,KU4,YEL2)

      endif

109   continue

C     CALCULATE KEEL VERTICAL STIFFNESS

      YPRIM3=-y+DELTA

      if (QD4 .eq. 0.0) goto 110
      if (QD4 .gt. 0.0) then

      CALL BILINALL(YPRIM3,-R,kvkb,RR5,KD5,QD4,KU5,YEL3,YMAX3,
     +  YMIN3,KY5,ZZ5,WZ5,WWW5,YYY5,UUU5)

      elseif (QD4 .lt. 0.0) then

      CALL RUBBER(YPRIM3,kvkb,RR5,KD5,QD4,KU5.YEL3)

      endif

110   continue


C     RECALCULATION OF DELTA

      if (QD3.ge.0.0.or.QD4.ge.0.0) then
        DELTA=weight/(2D0*kvs+kvk)
        goto 120
      endif
```

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D Line# 1      7
1   414         if (kvkb.eq.kvk) then
1   415           DELTA=weight/(2D0*kvs+kvk)
1   416         elseif (kvkb.gt.kvk) then
1   417           DELTA=YEL3+(weight-(YEL3*(2D0*kvs+kvk)))/(2D0*kvsp+kvkp)
1   418         endif
1   419
1   420 120     continue
1   421
1   422         if (QD1.eq.0.0.and.QD2.eq.0.0.and.QD3.eq.0.0.
1   423        +  and.QD4.eq.0.0) goto 111
1   424
1   425 C       RECALCULATION OF STIFFNESS MATRIX VALUES
1   426
1   427         k(1,1)=(2D0*Ks+2D0*khsb+khkb)
1   428         k(1,3)=(2D0*Ks*AAA+2D0*khsb*LLL*sin(alpha))
1   429         k(3,1)=k(1,3)
1   430         k(2,2)=(kvsb1+kvsb2+kvkb)
1   431         k(3,3)=(2D0*Ks*AAA**2D0+2D0*khsb*((LLL*sin(alpha))**2D0)+
1   432        +  ((kvsb1+kvsb2)*((LLL*cos(alpha))**2D0)-(weight*h)))
1   433
1   434 111      DO 3000,ll=0,5
2   435           A(ll)=0.0
2   436           B(ll)=0.0
2   437           C(ll)=0.0
2   438           D(ll)=0.0
2   439           E(ll)=0.0
2   440           F(ll)=0.0
2   441           G(ll)=0.0
2   442           HH(ll)=0.0
2   443 3000    CONTINUE
1   444         mm=mm+1
1   445            DO 302, NN=1,4
2   446          IF(NN.EQ.1) THEN
2   447           FF=0.0
2   448            ELSE IF (NN.EQ.2 .OR. NN.EQ.3) THEN
2   449           FF=5D-1
2   450          ELSE IF (NN.EQ.4) THEN
2   451           FF=1D0
2   452          ENDIF
2   453          A(NN)=dtau*(R+FF*D(NN-1))
2   454          B(NN)=dtau*(S+FF*E(NN-1))
2   455          C(NN)=dtau*(TAU+FF*F(NN-1))
2   456          D(NN)=dtau*((-cx(2,2)/m(2,2))*(R+FF*D(NN-1))-(k(2,2)/m(2,2))
2   457        +*(y+FF*A(NN-1))-amp*ampacc*acv(l)/2.54D0)
2   458          G(NN)=dtau*((-cx(1,1)/m(1,1))*(S+FF*E(NN-1))-(cx(1,3)/m(1,1))
2   459        +*(TAU+FF*F(NN-1))-(k(1,1)/m(1,1))*(x+FF*B(NN-1))
2   460        +-(k(1,3)/m(1,1))*(t+FF*C(NN-1))-ampacc*ac(l)/2.54D0)
2   461         HH(NN)=dtau*((-cx(3,3)/m(3,3))*(TAU+FF*F(NN-1))-(cx(3,1)/m(3,3))
2   462        +*(S+FF*E(NN-1))-(k(3,3)/m(3,3))*(t+FF*C(NN-1))+(m(3,1)/m(3,3))
2   463        +*((-cx(2,2)/m(2,2))*(R+FF*D(NN-1))-(k(2,2)/m(2,2))*(y+FF*A(NN-
2   464        +1)))*(t+FF*C(NN-1))
2   465        +-(k(3,1)/m(3,3))*(x+FF*B(NN-1))
2   466        +-(m(3,1)/m(3,3))*ampacc*ac(l)/2.54D0)
2   467
2   468         E(NN)=(m(1,1)*m(3,3)*G(NN)-m(1,3)*m(3,3)*HH(NN))/
2   469        +(m(3,3)*m(1,1)-m(1,3)*m(3,1))
2   470         F(NN)=(HH(NN)-(m(3,1)/m(3,3))*E(NN))
2   471 302     continue
1   472
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C     DETERMINING SYSTEM RESPONSE

      yold=y
      y=yold+(A(1)+2D0*A(2)+2D0*A(3)+A(4))/6D0

      xold=x
      x=xold+(B(1)+2D0*B(2)+2D0*B(3)+B(4))/6D0

      told=t
      t=told+(C(1)+2D0*C(2)+2D0*C(3)+C(4))/6D0

      R=R+(D(1)+2D0*D(2)+2D0*D(3)+D(4))/6D0

      S=S+(E(1)+2D0*E(2)+2D0*E(3)+E(4))/6D0

      TAU=TAU+(F(1)+2D0*F(2)+2D0*F(3)+F(4))/6D0

C     MAXIMUM VALUES FOR TRANSLATIONS AND ROTATION

      if (abs(xold).gt.abs(maxx)) then
       timex=dtau*(l-1)
       maxx=xold
      endif
      if (abs(told).gt.abs(maxt)) then
       timet=dtau*(l-1)
       maxt=told
      endif
      if (abs(yold).gt.abs(maxy)) then
       timey=dtau*(l-1)
       maxy=yold
      endif

C     CALCULATE VERTICAL AND HORIZONTAL FORCES CAUSED BY VESSEL,
C     TEST FOR FAILURE

C     CALCULATE FORCES ON SIDE/KEEL BLOCKS
      if (QD3.eq.0.0) then
      rf1=kvs*((weight/k(2,2))-yold-(LLL*cos(alpha))*told)
      rf2=kvs*((weight/k(2,2))-yold+(LLL*cos(alpha))*told)
      elseif (QD3.ne.0.0) then
            rf1=RR3
            rf2=RR4
      endif

      if (QD4.eq.0.0) then
      rf3=kvk*((weight/k(2,2))-yold)
      elseif (QD4.ne.0.0) then
            rf3=RR5
      endif

      if (QD2.eq.0.0) then
      hf1=khs*(xold+LLL*told*sin(alpha))
      hf2=khs*(xold+LLL*told*sin(alpha))
      elseif (QD2.gt.0.0) then
            hf1=RR2
            hf2=RR2
      endif

      if (QD1.eq.0.0) then
```

```
      hf3=khk*(xold)
      elseif (QD1.gt.0.0) then
           hf3=RR1
      endif

C     TEST FOR SIDE BLOCK SLIDING

      if (flag1.eq.1) then
       go to 400
      else if (hf1.lt.0.0.and.rf1.gt.0.0
     + .and. u1*rf1+hf1+u2*rf1*cos(beta)*sin(beta)
     + -rf1*cos(beta)*sin(beta) .lt. 0.0) then
       time1= dtau*(l-1)
       flag1=1
      else if (hf2.gt.0.0.and.rf2.gt.0.0
     + .and. -u1*rf2+hf2-u2*rf2*(cos(beta)*sin(beta))
     + +rf2*cos(beta)*sin(beta) .gt. 0.0) then
       time1=dtau*(l-1)
       flag1=1
      endif
      x1=xold
      y1=yold
      t1=told
400   continue

C     TEST FOR KEEL BLOCK SLIDING

      if (flag2.eq.1) then
       go to 410
      else if (rf3.gt.0.0.and.abs(hf3/rf3).gt.crit2) then
       time2=dtau*(l-1)
       flag2=1
      endif
      x2=xold
      y2=yold
      t2=told
410   continue
C     TEST FOR SIDE BLOCK OVERTURNING

      if (flag3.eq.1) then
       go to 420
      else if (hf1.lt.0.0.and.rf1.gt.0.0.and.abs(hf1/rf1).gt.crit3) then
       time3= dtau*(l-1)
       flag3=1
      else if (hf2.gt.0.0.and.rf2.gt.0.0.and.abs(hf2/rf2).gt.crit3) then
       time3=dtau*(l-1)
       flag3=1
      endif
      x3=xold
      y3=yold
      t3=told
420   continue

C     TEST FOR KEEL BLOCK OVERTURNING

      if (flag4.eq.1) then
       go to 430
      else if (rf3.gt.0.0.and.abs(hf3/rf3).gt.crit4) then
       time4=dtau*(l-1)
```

```
       flag4=1
      endif
      x4=xold
      y4=yold
      t4=told
  430 continue

C     TEST FOR SIDE BLOCK LIFTOFF

      if (flag5.eq.1) then
       go to 440
      else if (rf1.lt.0.0 .or. rf2.lt.0.0) then
       time5=dtau*(l-1)
       flag5=1
      endif
      x5=xold
      y5=yold
      t5=told
  440 continue

C     TEST FOR KEEL BLOCK LIFTOFF

      if (flag6.eq.1) then
       go to 450
      else if (rf3.lt.0.0) then
       time6=dtau*(l-1)
       flag6=1
      endif
      x6=xold
      y6=yold
      t6=told
  450 continue

C     TEST FOR SIDE BLOCK CRUSHING

      if (flag7.eq.1) then
       go to 460
      else if (rf1.gt.0.0 .and. (rf1/sidearea).gt.plside) then
       flag7=1
       time7=dtau*(l-1)

        else if (rf2.gt.0.0 .and. (rf2/sidearea).gt.plside) then
       flag7=1
       time7=dtau*(l-1)
      endif
      x7=xold
      y7=yold
      t7=told
  460 continue

C     TEST FOR KEEL BLOCK CRUSHING

      if (flag8.eq.1) then
       go to 470
      else if (rf3.gt.0.0 .and. (rf3/keelarea).gt.plkeel) then
       flag8=1
       time8=dtau*(l-1)
      endif
      x8=xold
```

```
      y8=yold
      t8=told
470   continue

C     CAPTURE OF DISPLACEMENT, ROTATION & RESISTANCE OUTPUT:

      if (dec.ne.'Y'.and.dec.ne.'y') goto 301
      xx(mm)=xold
      tt(mm)=told
      goto (501,502,503,504,505),decrr
501   if (QD1.eq.0.0) then
      rrr(mm)=hf3
      elseif (QD1.gt.0.0) then
      rrr(mm)=RR1
      endif
      yy(mm)=yold
      goto 506
502   if (QD2.eq.0.0) then
      rrr(mm)=hf1
      elseif (QD2.gt.0.0) then
      rrr(mm)=RR2
      xx(mm)=XPRIM
      endif
      yy(mm)=yold
      goto 506
503   if (QD3.eq.0.0) then
      rrr(mm)=rf1
      elseif (QD3.ne.0.0) then
      rrr(mm)=RR3
      endif
      yy(mm)=YPRIM1
      goto 506
504   if (QD3.eq.0.0) then
      rrr(mm)=rf2
      elseif (QD3.ne.0.0) then
      rrr(mm)=RR4
      endif
      yy(mm)=YPRIM2
      goto 506
505   if (QD4.eq.0.0) then
      rrr(mm)=rf3
      elseif (QD4.ne.0.0) then
      rrr(mm)=RR5
      endif
      yy(mm)=YPRIM3

506   continue

301   continue

      go to 999

60000 continue
      if(dec.ne.'Y'.and.dec.ne.'y') then
      write(*,'(A)') ' I AM FINISHING. '
      goto 20000
      endif

C     CREATION OF DISPLACEMENT, ROTATION, & RESISTANCE OUTPUT FILES:
```

```

      CALL RESPALL(xx,yy,tt,rrr,dtau)

998   go to 20000

999   CONTINUE

      if(ampacc.eq.1D0) then

        write(*,'(a)') ' ENTER OUTPUT FILENAME ...'
        read(*,'(a)') outfname
        open(46,file=outfname,status='new',form='formatted')


      write(46.4000) nsys
4000  format(1x,/,28x,'**** System ',I2,1x,'****')
      write(46,4050) hull
4050  format(1x,/,30x,'** Hull ',I3,1x,'**')
      write(46.4100)
4100  format(1x,//,28x,'* Ship Parameters *')
      write(46,4150)
4150  format(1x,/,5x,'Weight',8x,'Moment of Inertia',9x,'K.G.')
      write(46,4200) weight.Ik,h
4200  format(1x.f9.1,1x,'kips',1x,f11.1,1x,'kips-in-sec2',
     +3x,f6.1,1X,'ins')
      write(46,4250)
4250  format(1x,//,26x,'* Drydock Parameters *')
      write(46,4300)
4300  format(1x,/,1x,'Side Block Height',3x,'Side Block Width',
     +3x,'Keel Block Height',3x,'Keel Block Width')
      write(46,4350) htside,baseside,htkeel,basekeel
4350  format(2x,f6.1,1x,'ins',11x,f6.1,1x,'ins',11x,f6.1,1x,'ins',
     +9x,f6.1,1x,'ins')
      write(46,4400)
4400  format(1x,/,1x,'Side-to-Side Pier Distance',3x,'Wale Shore Ht.'
     + ,3x,'Wale Shore Stiffness',2x.'Cap Angle')
      write(46,4450) br,AAA,Ks,beta
4450  format(1x,t7,f6.1,1x,'ins'.17x,f6.1,1x,'ins',8x,f8.1,1x,
     + 'kips/in',1x,f5.3,1x,'rad')
      write(46,4470)
4470  format(1x,/,' 1Side Side Pier Contact Area'
     +,3x,'Total Keel Pier Contact Area',6X,'kkhp')
      write(46,4475) sidearea,keelarea,kkhp
4475  format(1x,8x,f11.1,1x,'in2',14x,f11.1,1x,'in2',10x,f7.1,1x,
     + 'kips/in')
      write(46,4500)
4500  format(1x,/,1x,'B/B Friction Coeff',3x,
     +'H/B Friction Coeff',5x,'kshp',10x,'kvsp')
      write(46,4550) u1,u2,kshp,kvsp
4550  format(6x,f7.3,13x,f7.3,7x,f7.1,1x,'kips/in',1x,f7.1,1x,
     +  'kips/in')
      write(46,4600)
4600  format(1x,/,1x,'Side Pier Fail Stress Limit',4x,'Keel Pier'
     +,' Fail Stress Limit',6x,'kvkp')
      write(46,4650) plside,plkeel,kvkp
4650  format(1x,10x,f7.3,1x,'kips/in2'15x,f7.3,1x,'kips/in2',
     + 6x,f7.1,1x,'kips/in')
      write(46,4700)
4700    format(1x,/,1x,'Side Pier Vertical Stiffness',3x,'Side Pier'.
```

```
       +' Horizontal Stiffness')
        write(46,4750) kvs,khs
  4750     format(1x,3x,f11.1,1x,'kips/in',11x,f11.1,1x,'kips/in')
           write(46,4775)
  4775     format(1x,/,1x,'Keel Pier Vertical Stiffness',3x,
       +'Keel Pier Horizontal Stiffness')
        write(46,4780) kvk,khk
  4780     format(1x,3x,f11.1,1x,'kips/in',11x,f11.1,1x,'kips/in')
        write(46,4782)
  4782  format(1x,/,6x,'QD1',17x,'QD2',18x,'QD3',17x,'QD4')
        write(46,4785) QD1,QD2,QD3,QD4
  4785  format(2x,f8.1,1x,'kips',7x,f8.1,1x,'kips',8x,f8.1,1x,'kips',
       +7x,f8.1,1x,'kips')
        write(46,4800)
  4800  format(1x,//,20x,'* System Parameters and Inputs *')
        write(46,4850) quakname
  4850     format(1x,/,1x,'Earthquake Used is ',A40)
        write(46,4852) hname
  4852  format(1x,/,1x,'Horizontal acceleration input is ',A40)
        write(46,4854) vname
  4854  format(1x,/,1x,'Vertical acceleration input is ',A40)
        write(46,4875)
  4875  format(1x,20x,' Earthquake Acceleration Time History.')

        write(46,4995)
  4995  format(1x,/,1x,'Vertical/Horizontal Ground Acceleration Ratio'
       +,3x,'Data Time Increment')
        write(46,4990) amp,dtau
  4990  format(1x,10x,f6.3,t55,f6.3,1X,'sec')
        write(46,4900)
  4900  format(1x,/,1x,'Gravitational Constant',3x,'% System Damping')
        write(46,4950) gravity,zeta*100.
  4950  format(1x,7x,f6.2,1x,'in/sec2',10x,f6.2,1x,'%')
        write(46,5000)
  5000  format(1x,/,25x,'Mass Matrix',/)
        do 5100 i=1,3
1       write(46,5050) m(i,1),m(i,2),m(i,3)
1 5050  format(1x,f15.4,5x,f15.4,5x,f15.4)
1 5100  continue
        write(46,5200)
  5200  format(1x,/,25x,'Damping Matrix',/)
        do 5300 i=1,3
1       write(46,5250) cx(i,1),cx(i,2),cx(i,3)
1 5250  format(1x,f15.4,5x,f15.4,5x,f15.4)
1 5300  continue
        write(46,5400)
  5400  format(1x,/,25x,'Stiffness Matrix',/)
        do 5500 i=1,3
1       write(46,5450) ko(i,1),ko(i,2),ko(i,3)
1 5450  format(1x,f15.4,5x,f15.4,5x,f15.4)
1 5500  continue
        write(46,5700)
  5700     format(1x,//)
        WRITE(46,6000)
  6000     FORMAT(1X,'Undamped Natural Frequencies',t35,'Mode #1',t50,
       +'Mode #2',t65,'Mode #3')
        write(46,6001) w1,w3,w2
  6001  format(1x,t31,f7.3,1x,'rad/sec',t46,f7.3,1x,'rad/sec',t62,f7.3,
       +' rad/sec')
```

```
      WRITE(46,6002)
6002    FORMAT(1X,'Damped Natural Frequencies',t35,'Mode #1',t50,
     +'Mode #2',t65,'Mode #3')
      WRITE(46,6500) w1*sqrt(1-zeta**2),w3*sqrt(1-zeta**2),
     +w2*sqrt(1-zeta**2)
6500  format(1x,t31,f7.3,1x,'rad/sec',t46,f7.3,1x,'rad/sec',t62,f7.3,
     +' rad/sec')
      endif

      write(46,10500) ampacc*100,quakname
10500   format(1x,///,1x,'For Earthquake Acceleration of ',f6.2,' % '
     +,'of the ',A40,/)

      write(46,25000)
25000   format(1x,'Maximums/Failures',t26,'X (ins)',t36,'Y (ins)',t51,
     +'Theta (rads)',t65,'Time (sec)')
      write(46,25001)
25001 format(1x,'-----------------',t25,'--------',t35,'--------',t50,
     +'-------------',t64,'-----------')
      write (46,310) maxx,timex
310   format (1x,' Maximum X',t25,f9.6,t65,f5.2)
      write (46,311) maxy,timey
 311  format (1x,' Maximum Y',t35,f9.6,t65,f5.2)
      write (46,312) maxt,timet
312   format (1x,' Maximum Rotation',t50,f9.6,t65,f5.2)

      if (flag1.eq.1) then
      flag10=flag10+1
       write (46,313) x1,y1,t1,time1
313   format (1x,'Side block sliding' ,t25,f9.6,t35,f9.6,t50,f9.6,
     +t65,f5.2)

      endif

      if (flag2.eq.1) then
      flag10=flag10+1
       write (46,314) x2,y2,t2,time2
314   format (1x,'Keel block sliding' ,t25,f9.6,t35,f9.6,t50,f9.6,
     +t65,f5.2)
      endif

      if (flag3.eq.1) then
      flag10=flag10+1
       write (46,315) x3,y3,t3,time3
315   format (1x,'Side block overturning' ,t25,f9.6,t35,f9.6,t50,f9.6,
     +t65,f5.2)
      endif

      if (flag4.eq.1) then
      flag10=flag10+1
       write (46,316) x4,y4,t4,time4
316   format (1x,'Keel block overturning' ,t25,f9.6,t35,f9.6,t50,f9.6,
     +t65,f5.2)
      endif

      if (flag5.eq.1) then
      flag10=flag10+1
       write (46,317) x5,y5,t5,time5
317   format (1x,'Side block liftoff' ,t25,f9.6,t35,f9.6,t50,f9.6,
```

```
     +t65,f5.2)
      endif

      if (flag6.eq.1) then
      flag10=flag10+1
       write (46,318) x6,y6,t6,time6
318   format (1x,'Keel block lift off' ,t25,f9.6,t35,f9.6,t50,f9.6,
     +t65,f5.2)
      endif

      if (flag7.eq.1) then
      flag10=flag10+1
       write (46,319) x7,y7,t7,time7
319   format (1x,'Side block crushing' ,t25,f9.6,t35,f9.6,t50,f9.6,
     +t65,f5.2)
      endif

      if (flag8.eq.1) then
      flag10=flag10+1
       write (46,320) x8,y8,t8,time8
320   format (1x,'Keel block crushing' ,t25,f9.6,t35,f9.6,t50,f9.6,
     +t65,f5.2)
      endif

      if(flag10.eq.0) then
      write(46,11000)
11000   format(1x,/,1x,'No failures occurred.')
      if(counter.eq.1.0 .and. flag10.eq.0) then
      go to 60000
      endif
      if(counter.eq.0.0) then
      ampacmax=ampacc
      ampacc=ampacc+1D-1
        counter=1.0
      write(*,'(A)') ' In secondary looping stage. '
      endif
      endif
      if(ampacc.le.ampacmax) go to 20000
      if(counter.eq.1.0) then
      ampacc=ampacc-1D-2
      else if(counter.eq.0.0) then
      ampacc=ampacc-1D-1
      endif
      go to 10000
20000 continue
      stop
      end
```

```
Name     Type         Offset P Class

A       REAL*8         48946
AAA     REAL*8         49082
ABS                              INTRINSIC
AC      REAL           32882
ACLFNA  CHAR*40        *****
ACV     REAL           40890
ALPHA   REAL*8         49344
AMP     REAL*8         49496
AMPACC  REAL*8         49656
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AMPACM REAL*8          49672
ASIN                          INTRINSIC
B      REAL*8          48898
BASE   REAL*8          *****
BASEKE REAL*8          49170
BASESI REAL*8          49162
BBB    REAL*8          49352
BETA   REAL*8          49258
BR     REAL*8          49210
C      REAL*8          32834
CCC    REAL*8          49360
COS                           INTRINSIC
COUNTE REAL*8          49664
CRIT2  REAL*8          49632
CRIT3  REAL*8          49640
CRIT4  REAL*8          49648
CX     REAL*8          32658
D      REAL*8          32786
DEC    CHAR*40         49282
DECRR  INTEGER*2       49322
DECV   CHAR*40         *****
DELTA  REAL*8          49812
DTAU   REAL*8          49504
E      REAL*8          32562
F      REAL*8          32610
FF     REAL            50266
FLAG1  INTEGER*2       49680
FLAG10 INTEGER*2       49696
FLAG2  INTEGER*2       49682
FLAG3  INTEGER*2       49684
FLAG4  INTEGER*2       49686
FLAG5  INTEGER*2       49688
FLAG6  INTEGER*2       49690
FLAG7  INTEGER*2       49692
FLAG8  INTEGER*2       49694
G      REAL*8          32514
GRAVIT REAL*8          49154
H      REAL*8          49042
HF1    REAL*8          50318
HF2    REAL*8          50326
HF3    REAL*8          50334
HH     REAL*8          32466
HNAME  CHAR*40         49552
HTKEEL REAL*8          49186
HTSIDE REAL*8          49178
HULL   INTEGER*2       49254
I      INTEGER*2       49324
IK     REAL*8          49050
J      INTEGER*2       49326
K      REAL*8          32338
KD1    REAL*8          49844
KD2    REAL*8          49924
KD3    REAL*8          50004
KD4    REAL*8          50068
KD5    REAL*8          50148
KEELAR REAL*8          49242
KHK    REAL*8          49106
KHKB   REAL*8          49852
KHS    REAL*8          49098
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KHSB    REAL*8          49932
KKHP    REAL*8          49122
KO      REAL*8          32210
KS      REAL*8          49090
KSHP    REAL*8          49114
KU1     REAL*8          49836
KU2     REAL*8          49916
KU3     REAL*8          49996
KU4     REAL*8          50060
KU5     REAL*8          50140
KVK     REAL*8          49074
KVKB    REAL*8          49828
KVKP    REAL*8          49274
KVS     REAL*8          49058
KVSB1   REAL*8          49820
KVSB2   REAL*8          50076
KVSP    REAL*8          49066
KY1     INTEGER*2       49860
KY2     INTEGER*2       49940
KY3     INTEGER*2       50012
KY4     INTEGER*2       50084
KY5     INTEGER*2       50156
L       INTEGER*2       50204
LL      INTEGER*2       50262
LLL     REAL*8          49336
M       REAL*8          32082
MASS    REAL*8          49328
MAXT    REAL*8          49706
MAXX    REAL*8          49698
MAXY    REAL*8          49714
MIN                             INTRINSIC
MM      INTEGER*2       49722
MMANG1  REAL*8          49440
MMANG3  REAL*8          49456
MMMMM1  REAL*8          49464
MMMMM2  REAL*8          49472
MMMMM3  REAL*8          49480
MMMMM4  REAL*8          49488
MMX1    REAL*8          49432
MMX3    REAL*8          49448
MODE1   REAL*8          49416
MODE3   REAL*8          49424
N       INTEGER*2       *****
NN      INTEGER*2       50264
NSYS    INTEGER*2       49256
OUTFNA  CHAR*40         50502
PLKEEL  REAL*8          49226
PLSIDE  REAL*8          49218
QD1     REAL*8          49130
QD2     REAL*8          49138
QD3     REAL*8          49146
QD4     REAL*8          49266
QUAKNA  CHAR*40         49512
R       REAL*8          49772
RF1     REAL*8          50294
RF2     REAL*8          50302
RF3     REAL*8          50310
RR1     REAL*8          49886
RR2     REAL*8          49966
```

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RR3     REAL*8        50030
RR4     REAL*8        50110
RR5     REAL*8        50174
RRR     REAL          24074
S       REAL*8        49780
SBFNAM  CHAR*40       48994
SIDEAR  REAL*8        49234
SIN                           INTRINSIC
SQRT                          INTRINSIC
T       REAL*8        49740
T1      REAL          50358
T2      REAL          50378
T3      REAL          50398
T4      REAL          50418
T5      REAL          50438
T6      REAL          50458
T7      REAL          50478
T8      REAL          50498
TAU     REAL*8        49788
TIME    REAL*8        *****
TIME1   REAL*8        50342
TIME2   REAL*8        50362
TIME3   REAL*8        50382
TIME4   REAL*8        50402
TIME5   REAL*8        50422
TIME6   REAL*8        50442
TIME7   REAL*8        50462
TIME8   REAL*8        50482
TIMET   REAL*8        50278
TIMEX   REAL*8        50270
TIMEY   REAL*8        50286
TOLD    REAL*8        49764
TT      REAL          16066
U1      REAL*8        49194
U2      REAL*8        49202
UUU1    INTEGER*2     49914
UUU2    INTEGER*2     49994
UUU3    INTEGER*2     50058
UUU4    INTEGER*2     50138
UUU5    INTEGER*2     50202
VEL     REAL*8        50214
VEL1    REAL*8        50230
VEL2    REAL*8        50246
VFNAME  CHAR*40       *****
VNAME   CHAR*40       49592
W1      REAL*8        49376
W12     REAL*8        49368
W2      REAL*8        49392
W22     REAL*8        49384
W3      REAL*8        49408
W32     REAL*8        49400
WEIGHT  REAL*8        49034
WWW1    INTEGER*2     49910
WWW2    INTEGER*2     49990
WWW3    INTEGER*2     50054
WWW4    INTEGER*2     50134
WWW5    INTEGER*2     50198
WZ1     REAL*8        49902
WZ2     REAL*8        49982
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WZ3     REAL*8          50046
WZ4     REAL*8          50126
WZ5     REAL*8          50190
X       REAL*8          49724
X1      REAL            50350
X2      REAL            50370
X3      REAL            50390
X4      REAL            50410
X5      REAL            50430
X6      REAL            50450
X7      REAL            50470
X8      REAL            50490
XEL1    REAL*8          49862
XEL2    REAL*8          49942
XMAX1   REAL*8          49870
XMAX2   REAL*8          49950
XMIN1   REAL*8          49878
XMIN2   REAL*8          49958
XOLD    REAL*8          49748
XPRIM   REAL*8          50206
XSCL    REAL*8          16018
XX      REAL                2
Y       REAL*8          49732
Y1      REAL            50354
Y2      REAL            50374
Y3      REAL            50394
Y4      REAL            50414
Y5      REAL            50434
Y6      REAL            50454
Y7      REAL            50474
Y8      REAL            50494
YEL1    REAL*8          49796
YEL2    REAL*8          50086
YEL3    REAL*8          49804
YMAX1   REAL*8          50014
YMAX2   REAL*8          50094
YMAX3   REAL*8          50158
YMIN1   REAL*8          50022
YMIN2   REAL*8          50102
YMIN3   REAL*8          50166
YOLD    REAL*8          49756
YPRIM1  REAL*8          50222
YPRIM2  REAL*8          50238
YPRIM3  REAL*8          50254
YY      REAL             8010
YYY1    INTEGER*2       49912
YYY2    INTEGER*2       49992
YYY3    INTEGER*2       50056
YYY4    INTEGER*2       50136
YYY5    INTEGER*2       50200
ZETA    REAL            49250
ZZ1     REAL*8          49894
ZZ2     REAL*8          49974
ZZ3     REAL*8          50038
ZZ4     REAL*8          50118
ZZ5     REAL*8          50182
```

```
                                                                  16:50:34
D Line# 1      7    .                         Microsoft FORTRAN77 V3.20 02/84

Name     Type          Size   Class

ACCLIN                        SUBROUTINE
BILINA                        SUBROUTINE
MAIN                          PROGRAM
RESPAL                        SUBROUTINE
RUBBER                        SUBROUTINE


 Pass One     No Errors Detected
             932 Source Lines
```

"BILINALL" and "RUBBER" Subroutine Listings. . . . .

```
                                                                    Page   1
                                                                    01-20-88
                                                                    11:06:38
D Line# 1     7                             Microsoft FORTRAN77 V3.20 02/84
$debug
$title:  'bilinall'
$storage: 2
$nofloatcalls


C-----------------------------------------------------------------------

C     SUBROUTINE WHICH CALCULATES THE BILINEAR HORIZONTAL
C      OR VERTICAL STIFFNESS AND RESISTANCE

C-----------------------------------------------------------------------

      SUBROUTINE BILINALL(U,V,PK,RR,KD,QD,KU,UEL,UMAX,UMIN,KY,ZZ,WZ,
     +  WWW,YYY,UUU)

      real*8 U,V,RR,KD,QD,KU,UEL,PK
      real*8 UMAX,UMIN,ZZ,WZ
      integer WWW,YYY,UUU,KY

C     BEGINNING OF BILINEAR LOGIC

C     CHECK IF RESPONSE STILL ON INITIAL ELASTIC LINE

        if (KY .lt. 0) goto 4040
        if (KY .gt. 0) goto 3480
        RR=KU*U
        PK=KU

C      CHECK IF THE RESPONSE HAS GONE PLASTIC

        if (U .gt. -UEL .and. U .lt. UEL) goto 4720

C      RESPONSE IS NOW PLASTIC

        if (U .lt. -UEL) goto 4040

C      RESPONSE IS ON THE TOP PLASTIC LINE

3220    KY=1
        PK=KD
        RR=KD*U+QD
        WWW=0
        YYY=0
        ZZ=0.0
        goto 4720

```

```
C      CHECK IF VELOCITY SHIFTS FROM POSITIVE TO NEGATIVE

3480    if (V .gt. 0) goto 3720

C      CHECK IF ON THE RIGHT ELASTIC LINE

        if (YYY .gt. 0) goto 3630

C      CALCULATE VALUE OF UMAX

        ZZ=U
3630    YYY=1
        UMAX=ZZ

C      CHECK IF RESPONSE SHIFTS TO LOWER PLASTIC LINE

3720    if (U .lt. (UMAX-2*UEL)) goto 4040

C      CHECK IF RESPONSE SHIFTS TO TOP PLASTIC LINE

        if (U .gt. UMAX) goto 3220

C      CHECK IF RESPONSE RETURNS TO TOP PLASTIC LINE

        if (YYY .eq. 0) goto 3220

C      RESPONSE IS ON THE RIGHT ELASTIC LINE

        KY=1
        PK=KU
        RR=KU*U+(KD-KU)*UMAX+QD
        goto 4720

C      CHECK IF VELOCITY SHIFTS TO POSITIVE

4040    if (V .gt. 0) goto 4350

C      CHECK IF RESPONSE REMAINS ELASTIC

        if (WWW .eq. 1) goto 4350

C      RESPONSE IS ON THE BOTTOM PLASTIC LINE

4150    KY=-1
        PK=KD
        RR=KD*U-QD
        UUU=0
        WZ=0.0
        goto 4720

```

```
C      CHECK IF RESPONSE IS ON THE LEFT ELASTIC LINE

4350    if (UUU .gt. 0) goto 4370
        WZ=U
4370    UUU=1
        UMIN=WZ

C      CHECK IF RESPONSE RETURNS TO TOP PLASTIC LINE

        if (U .gt. (UMIN+2*UEL)) goto 3220

C      CHECK IF RESPONSE RETURNS TO BOTTOM PLASTIC LINE

        if (U .lt. UMIN) goto 4150

C      RESPONSE IS ON THE LEFT ELASTIC LINE

        WWW=1
        RR=KU*U+(KD-KU)*UMIN-QD
        PK=KU

4720  continue
      RETURN
      END

Name    Type        Offset P Class

KD     REAL*8          16 *
KU     REAL*8          24 *
KY     INTEGER*2       40 *
PK     REAL*8           8 *
QD     REAL*8          20 *
RR     REAL*8          12 *
U      REAL*8           0 *
UEL    REAL*8          28 *
UMAX   REAL*8          32 *
UMIN   REAL*8          36 *
UUU    INTEGER*2       60 *
V      REAL*8           4 *
WWW    INTEGER*2       52 *
WZ     REAL*8          48 *
YYY    INTEGER*2       56 *
ZZ     REAL*8          44 *



Name    Type          Size   Class

BILINA                       SUBROUTINE


 Pass One    No Errors Detected
           121 Source Lines
```

```
                                                                    Page   1
                                                                    01-29-88
                                                                    16:45:08
D Line# 1     7                                 Microsoft FORTRAN77 V3.20 02/84
      1 $debug
      2 $title:  'rubber'
      3 $nofloatcalls
      4
      5
      6 C-----------------------------------------------------------------
      7
      8 C     SUBROUTINE WHICH CALCULATES THE RUBBER CAP VERTICAL
      9 C      STIFFNESS AND RESISTANCE
     10
     11 C-----------------------------------------------------------------
     12
     13       SUBROUTINE RUBBER(U,PK,RR,KD,QD,KU,UEL)
     14
     15       real*8 U,RR,KD,QD,KU,UEL,PK
     16
     17 C     BEGINNING OF RUBBER LOGIC
     18
     19 C     CHECK IF RESPONSE STILL ON INITIAL ELASTIC LINE
     20
     21         if (U .gt. UEL) goto 3220
     22         RR=KU*U
     23         PK=KU
     24         goto 4720
     25
     26 C      RESPONSE IS ON THE 2ND ELASTIC LINE
     27
     28 3220    continue
     29         PK=KD
     30         RR=KD*U+QD
     31
     32 4720  continue
     33       RETURN
     34       END

Name    Type        Offset P Class

KD     REAL*8           12 *
KU     REAL*8           20 *
PK     REAL*8            4 *
QD     REAL*8           16 *
RR     REAL*8            8 *
U      REAL*8            0 *
UEL    REAL*8           24 *
```

Sample Input Data File and Output File

```
    ***SHIP/SUB DRYDOCK BLOCKING SYSTEM***  DATA FILE: A:S1ORBILN.DAT

          ***INPUT FILE DATA***


SHIP NAME:   LAFAYETTE SSBN 616
DISCRIPTION OF ISOLATORS IF USED: NO ISOLATOR ALL BILINEAR
DISCRIPTION OF BUILDUP: 8 SPACING COMPOSITE
DISCRIPTION OF WALE SHORES USED: NO WALE SHORES
DISCRIPTION OF DAMPING: 5 % DAMPING
LOCATION OF DRYDOCK BEING STUDIED: NO SPECIFIC LOCATION
NAVSEA DOCKING DRAWING NUMBER: 845-2006640
REFERENCE SPREADSHEET STIFFNESS CALC FILE NAME: S1KHORI6.WK1 & S1SHORI6.WK1
MISC. COMMENTS: S1ORBILN.DAT  1839 4 MAR 88

SHIP WEIGHT  (KIPS)                                  W= 16369.9
HEIGHT OF KG (IN)                                    H= 193
MOMENT OF INERTIA  (KIPS*IN*SEC^2)                  Ik= 2410451
SIDE PIER VERTICAL STIFFNESS (KIPS/IN)             Kvs= 10113.39
SIDE PIER VERTICAL PLASTIC STIFFNESS (KIPS/IN)    Kvsp= 4025.64
KEEL PIER VERTICAL STIFFNESS (KIPS/IN)             KVK= 46808.74
KEEL PIER VERTICAL PLASTIC STIFFNESS(KIPS/IN)     KVKP= 46808.74
HEIGHT OF WALE SHORES  (IN)                        AAA= 0
WALE SHORE STIFFNESS (KIPS/IN)                      KS= 0
SIDE PIER HORIZONTAL STIFFNESS (KIPS/IN)           KHS= 5825.13
KEEL PIER HORIZONTAL STIFFNESS (KIPS/IN)           KHK= 59223.08
SIDE PIER HORIZONTAL PLASTIC STIFFNESS(KIPS/IN) KSHP= 2212.17
KEEL PIER HORIZONTAL PLASTIC STIFFNESS(KIPS/IN) KKHP= 38434.86
RESTORING FORCE AT 0 DEFLECT KEEL HORIZ   (KIPS) QD1= 18098.07
RESTORING FORCE AT 0 DEFLECT SIDE HORIZ   (KIPS) QD2= 4817.6
RESTORING FORCE AT 0 DEFLECT SIDE VERT    (KIPS) QD3= 2262.37
RESTORING FORCE AT 0 DEFLECT KEEL VERT    (KIPS) QD4= 0
GRAVITATIONAL CONSTANT (IN/SEC^2)                GRAV= 386.09

SIDE BLOCK WIDTH  (IN)                             SBW= 42
KEEL BLOCK WIDTH  (IN)                             KBW= 48
SIDE BLOCK HEIGHT (IN)                             SBH= 74
KEEL BLOCK HEIGHT (IN)                             KBH= 60
BLOCK ON BLOCK FRICTION COEFFICIENT                 U1= .43
HULL ON BLOCK FRICTION COEFFICIENT                  U2= .53
SIDE PIER TO SIDE PIER TRANSVERSE DISTANCE (IN)     BR= 144
SIDE PIER CAP PROPORTIONAL LIMIT                  SCPL= .7
KEEL PIER CAP PROPORTIONAL LIMIT                  KCPL= .45
TOTAL SIDE PIER CONTACT AREA (ONE SIDE) (IN^2) SAREA= 8352
TOTAL KEEL PIER CONTACT AREA   (IN^2)         KAREA= 55440
PERCENT CRITICAL DAMPING                          ZETA= .05
HULL NUMBER (XXXX)                                HULL= 616
SYSTEM NUMBER (XXX)                               NSYS= 1
CAP ANGLE (RAD)                                   BETA= .377
```

```
 16369.9 193.0 2410451  10113.39   4025.64  46808.74   0.0      0.0
   5825.13  59223.09   2212.17  38434.86 18098.07  4817.60  2262.37 386.09
  42.00  48.00  74.00  60.00 0.43 0.53
  144.00 0.70 0.45   8352.0  55440.0 0.050
  616   1 0.377      0.00  46808.74
```

```
LAFAYETTE SSBN 616
NO ISOLATOR ALL BILINEAR
8 SPACING COMPOSITE
NO WALE SHORES
5 % DAMPING
NO SPECIFIC LOCATION
845-2006640
S1KHORIG.WK1 & S1SHORIG.WK1
S1ORBILN.DAT  1839 4 MAR 88
```

```
                             **** System  1 ****

                               ** Hull 616 **


                             * Ship Parameters *

   Weight          Moment of Inertia          K.G.
 16369.9 kips   2410451.0 kips-in-sec2    193.0 ins


                            * Drydock Parameters *

Side Block Height   Side Block Width   Keel Block Height   Keel Block Width
   74.0 ins            42.0 ins            60.0 ins            48.0 ins

Side-to-Side Pier Distance   Wale Shore Ht.   Wale Shore Stiffness  Cap Angle
      144.0 ins                     .0 ins              .0 kips/in  .377 rad

1Side Side Pier Contact Area   Total Keel Pier Contact Area      kkhp
             8352.0 in2                 55440.0 in2         38434.9 kips/in

B/B Friction Coeff   H/B Friction Coeff      kshp           kvsp
       .430                 .530        2212.2 kips/in  4025.6 kips/in

Side Pier Fail Stress Limit    Keel Pier Fail Stress Limit      kvkp
             .700 kips/in2                .450 kips/in2     46808.7 kips/in

Side Pier Vertical Stiffness   Side Pier Horizontal Stiffness
      10113.4 kips/in                5825.1 kips/in

Keel Pier Vertical Stiffness   Keel Pier Horizontal Stiffness
      46808.7 kips/in               59223.1 kips/in

     QD1                 QD2                 QD3                 QD4
  18098.1 kips        4817.6 kips         2262.4 kips            .0 kips


                       * System Parameters and Inputs *

Earthquake Used is 1940 EL CENTRO

Horizontal acceleration input is HORIZONTAL

Vertical acceleration input is
                     Earthquake Acceleration Time History.

Vertical/Horizontal Ground Acceleration Ratio   Data Time Increment
          1.000                                         .010 sec

Gravitational Constant   % System Damping
      386.09 in/sec2            5.00 %
```

```
                        Mass Matrix

        42.3992               .0000           8183.0420
          .0000             42.3992               .0000
      8183.0420               .0000        2410451.0000

                        Damping Matrix

       118.1018               .0000           5027.6454
          .0000            168.5898               .0000
      5027.6454               .0000        1549181.3597

                        Stiffness Matrix

     70873.3400               .0000         163103.6400
          .0000          67035.5200               .0000
    163103.6400               .0000       99931610.6070


Undamped Natural Frequencies     Mode #1        Mode #2        Mode #3
                               6.425 rad/sec 69.650 rad/sec  39.763 rad/sec
Damped Natural Frequencies       Mode #1        Mode #2        Mode #3
                               6.416 rad/sec 69.563 rad/sec  39.713 rad/sec


For Earthquake Acceleration of 100.00 % of the 1940 EL CENTRO

Maximums/Failures       X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------      --------  --------       ------------- -----------
 Maximum X               -.243397                               11.22
 Maximum Y                         -.202029                      8.01
 Maximum Rotation                                  .048797      14.44
Side block sliding       -.103557   .033213       -.021226       6.24
Keel block sliding       -.095723   .021787       -.021704       6.23
Side block overturning    .082442  -.061166        .011885       5.61
Keel block overturning    .020383   .052877        .001717       4.71
Side block liftoff       -.007883  -.103857       -.003915       4.96
Side block crushing      -.009432   .021336        .009388       5.46
```

```
For Earthquake Acceleration of  90.00 % of the 1940 EL CENTRO

Maximums/Failures       X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------      --------  --------       ------------- -----------
 Maximum X              -.246421                               16.51
 Maximum Y                        -.181860                      8.01
 Maximum Rotation                                -.049806      13.83
Side block sliding       .000484  -.055408        .002296       5.77
Keel block sliding      -.087291   .019017       -.019629       6.23
Side block overturning   .000484  -.055408        .002296       5.77
Keel block overturning  -.031319  -.030563        .001947       4.75
Side block liftoff      -.002232  -.081113       -.003868       4.97
Side block crushing     -.011740  -.012852        .009220       5.48
```

```
For Earthquake Acceleration of  80.00 % of the 1940 EL CENTRO

Maximums/Failures       X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------      --------  --------       ------------- -----------
 Maximum X              -.250337                               16.51
 Maximum Y                        -.161793                      8.01
 Maximum Rotation                                 .049040      19.75
Side block sliding       .000027  -.051407        .001472       5.77
Keel block sliding      -.088423   .009133       -.017334       6.22
Side block overturning   .000027  -.051407        .001472       5.77
Keel block overturning  -.021642   .058728       -.005154       5.03
Side block liftoff       .001236  -.051243       -.003723       4.98
Side block crushing      .008197  -.014721        .008773       5.50
```

```
For Earthquake Acceleration of  70.00 % of the 1940 EL CENTRO

Maximums/Failures       X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------      --------  --------       ------------- -----------
 Maximum X              -.248603                               13.79
 Maximum Y                        -.145349                      8.01
 Maximum Rotation                                 .049499      14.38
Side block sliding      -.026676   .040248       -.009791       6.28
Keel block sliding      -.083862   .039448       -.019523       7.37
Side block overturning  -.018619   .034936       -.011260       6.26
Keel block overturning  -.029241  -.004233        .007959       5.54
Side block liftoff      -.000110  -.023437       -.003463       4.99
Side block crushing     -.011305  -.039360       -.008468       5.92
```

```
For Earthquake Acceleration of  60.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)    Y (ins)        Theta (rads)  Time (sec)
-----------------       --------   --------       ------------- -----------

 Maximum X              -.252173                                  13.78
 Maximum Y                         -.116732                        8.00
 Maximum Rotation                                   .049920       19.65
Side block sliding      -.003131    .021628        -.004153        6.30
Keel block sliding       .061008    .097166         .017490        7.93
Side block overturning  -.036400    .021380        -.007884        6.24
Keel block overturning   .022516    .054039         .004804        5.42
Side block liftoff      -.003402    .000282        -.003089        5.00
Side block crushing      .001256   -.018646        -.008745        5.96
```

```
For Earthquake Acceleration of  50.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)    Y (ins)        Theta (rads)  Time (sec)
-----------------       --------   --------       ------------- -----------

 Maximum X               .246529                                  19.66
 Maximum Y                         -.094418                        8.00
 Maximum Rotation                                   .049232       19.61
Side block sliding      -.015797    .008866        -.002023        6.31
Keel block sliding      -.093131   -.025568        -.026015        8.50
Side block overturning  -.015797    .008866        -.002023        6.31
Keel block overturning   .029000    .008726         .004903        5.52
Side block liftoff      -.014161    .033488        -.003067        5.03
Side block crushing     -.000834   -.062532         .008307        6.50
```

```
For Earthquake Acceleration of  40.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)    Y (ins)        Theta (rads)  Time (sec)
-----------------       --------   --------       ------------- -----------

 Maximum X               .241724                                  19.55
 Maximum Y                         -.071379                        8.00
 Maximum Rotation                                   .048794       19.50
Side block sliding       .032752    .002736         .006452        7.86
Keel block sliding       .084762    .009522         .023788        9.05
Side block overturning   .008986    .014682        -.001517        7.34
Keel block overturning   .027507    .013162         .007261        6.60
Side block liftoff      -.004834    .006973         .002687        5.38
Side block crushing      .000491   -.013729         .009022        7.53
```

```
For Earthquake Acceleration of  30.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------       --------  --------       ------------- -----------
 Maximum X              -.031730                                   8.07
 Maximum Y                        -.040973                         8.00
 Maximum Rotation                                 .005341          7.51
Keel block overturning  -.028676   .012919       -.003477          8.06
Side block liftoff      -.009727   .017853       -.002363          5.84


For Earthquake Acceleration of  20.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------       --------  --------       ------------- -----------
 Maximum X              -.018083                                   7.97
 Maximum Y                        -.026897                         8.00
 Maximum Rotation                                 .003646          7.50
Side block liftoff       .002507   .019660        .002589          6.42


For Earthquake Acceleration of  10.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------       --------  --------       ------------- -----------
 Maximum X              -.008056                                   7.98
 Maximum Y                        -.013437                         4.79
 Maximum Rotation                                 .001623          7.45

No failures occurred.


For Earthquake Acceleration of  19.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------       --------  --------       ------------- -----------
 Maximum X              -.017166                                   7.97
 Maximum Y                        -.025552                         8.00
 Maximum Rotation                                 .003456          7.50
Side block liftoff       .002767   .020286        .002591          6.43
```

```
For Earthquake Acceleration of  18.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------       --------  --------       ------------- -----------
 Maximum X              -.015413                                  7.97
 Maximum Y                        -.024186                        4.79
 Maximum Rotation                                  .003294        7.49
Side block liftoff       .010977  -.002288         .002979        6.54


For Earthquake Acceleration of  17.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------       --------  --------       ------------- -----------
 Maximum X              -.014521                                  7.97
 Maximum Y                        -.022842                        4.79
 Maximum Rotation                                  .003091        7.49
Side block liftoff      -.002400  -.002636        -.002636        6.99


For Earthquake Acceleration of  16.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------       --------  --------       ------------- -----------
 Maximum X              -.013572                                  7.97
 Maximum Y                        -.021499                        4.79
 Maximum Rotation                                  .002858        7.49
Side block liftoff      -.003316   .016301        -.002449        7.90


For Earthquake Acceleration of  15.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------       --------  --------       ------------- -----------
 Maximum X               .013488                                  7.53
 Maximum Y                        -.020155                        4.79
 Maximum Rotation                                  .002624        7.48

No failures occurred.
```

APPENDIX 2

1. Sample Vertical and Horizontal Stiffness Spreadsheets

Sample Vertical and Horizontal Stiffness Spreadsheets. . . . .

```
VERTICAL STIFFNESS CALCULATIONS FOR DRYDOCK BLOCKS

HULL TYPE   616    DOCKING PLAN # =     845-2006640

SYSTEM #        30            KEEL BLOCKS           1" RUBBER CAP E1

BLOCK SPA    16.00 FEET

VERTICAL STIFFNESS:
-----------------------------------------------------------------------------------------------
                                                                                        PIER
 LEVEL  MATERIAL      E       LENGTH      WIDTH       HEIGHT        K            I/K     TOTAL K
   #                (PSI)      (IN)       (IN)         (IN)      (KIPS/IN)              (KIPS/IN)
-----------------------------------------------------------------------------------------------
                             (DEPTH)  (TRANSVERSE)
                               (B)        (H)          (L)


   1     RUBBER      992.00    42.00       24.00        1.00       999.94   0.0010001    459.76
   2     D.FUR     12539.19    42.00       24.00        4.00      3159.88   0.0003165
   3      OAK      23980.00    42.00       33.67       29.00      1169.35   0.0008552
   4    CONCRETE 4000000.00    42.00       48.00       27.00    298666.67   0.0000033
                                                       61.00
                    1845.83
                                                #                                    TOTAL STIFF
                                              BLOCKS               55                OF BLOCK SY
                                                                                     (KIPS/IN):

                                                                                      25286.68
```

```
      03-Feb-88

HORIZONTAL STIFFNESS MATRIX FOR 4 LAYERS        1" RUBBER CAP EI

SYSTEM 30
THIS IS A SIDE BLOCK SYSTEM FOR HULL 616 WITH 5 FT BUILDUP
16 FOOT CENTERS


  ELEMENT # 1    CONCRETE
                    DEPTH       TRANSVERSE                   HEIGHT
       E1             B1            H1           I1            L1
      (PSI)          (IN)          (IN)        (IN^4)         (IN)
  ------------------------------------------------------------------

        4000000            48            42       296352            48

  ------------------------------------------------------------------

  12E1I1/L1^3   6E1I1/L1^2    4E1I1/L1       2E1I1/L1
  ------------------------------------------------------------------

      128625000     3087000000    98784000000    49392000000
  ------------------------------------------------------------------

    RIGIDITY        TOP          SHEAR        ELEMENT
      G1r         CONTACT        STRAIN        SHEAR
     (PSI)         AREA         (IN/IN)      DEFLECTION
                  (IN^2)                        (IN)
  ------------------------------------------------------------------

       2400000           2016   0.0000002067   0.0000099206

  ------------------------------------------------------------------


  ELEMENT # 2    OAK
                    DEPTH       TRANSVERSE                   HEIGHT
       E2             B2            H2           I2            L2
      (PSI)          (IN)          (IN)        (IN^4)         (IN)
  ------------------------------------------------------------------

         335720          23.4          29.7   51086.24235            20

  ------------------------------------------------------------------

  12E2I2/L2^3   6E2I2/L2^2    4E2I2/L2       2E2I2/L2
  ------------------------------------------------------------------

    25726009.923   257260099.23   3430134656.3   1715067328.2
  ------------------------------------------------------------------

    RIGIDITY        TOP          SHEAR        ELEMENT
      G1r         CONTACT        STRAIN        SHEAR
     (PSI)         AREA         (IN/IN)      DEFLECTION
                  (IN^2)                        (IN)
```

```
--------------------------------------------------------------------------

        23980       486.486  0.0000857197   0.0017143933

--------------------------------------------------------------------------

ELEMENT # 3    DOUGLAS FIR
                  DEPTH        TRANSVERSE                       HEIGHT
     E3            B3             H3             I3              L3
   (PSI)          (IN)           (IN)          (IN^4)           (IN)
--------------------------------------------------------------------------

        95297            12             24          13824              6

--------------------------------------------------------------------------

12E3I3/L3^3    6E3I3/L3^2     4E3I3/L3        2E3I3/L3
--------------------------------------------------------------------------

   7.3188E+07     2.1956E+08     8.7826E+08     4.3913E+08
--------------------------------------------------------------------------

   RIGIDITY          TOP           SHEAR          ELEMENT
     GIr           CONTACT        STRAIN           SHEAR
    (PSI)           AREA          (IN/IN)        DEFLECTION
                   (IN^2)                          (IN)
-------------------------------------------------------------

         6807           288  0.0005101012    0.003060607

--------------------------------------------------------------------------


ELEMENT # 4    RUBBER
                  DEPTH        TRANSVERSE                       HEIGHT
     E4            B4             H4             I4              L3
   (PSI)          (IN)           (IN)          (IN^4)           (IN)
--------------------------------------------------------------------------

          992            12             24          13824              1

--------------------------------------------------------------------------

12E4I4/L4^3    6E4I4/L4^2     4E4I4/L4        2E4I4/L4
--------------------------------------------------------------------------

   1.6456E+08     8.2280E+07     5.4854E+07     2.7427E+07
--------------------------------------------------------------------------

   RIGIDITY          TOP           SHEAR          ELEMENT
     GIr           CONTACT        STRAIN           SHEAR          TOTAL
    (PSI)           AREA          (IN/IN)        DEFLECTION        SHEAR
                   (IN^2)                          (IN)       DEFLECTION (IN)
--------------------------------------------------------------------------

          335           288  0.0103556924   0.0103556924     1.5141E-02
```

```
F/                                    STIFFNESS MATRIX
M                                                                                                          D


Q1   1.2862E+08   3.0870E+09  -1.2862E+08   3.0870E+09   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00    0.0000E+00    0.0000E+00 q1

M1   3.0870E+09   9.8784E+10  -3.0870E+09   4.9392E+10   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00    0.0000E+00    0.0000E+00 th1

Q2  -1.2862E+08  -3.0870E+09   1.5435E+08  -2.8297E+09  -2.5726E+07   2.5726E+08   0.0000E+00   0.0000E+00    0.0000E+00    0.0000E+00 q2

M2   3.0870E+09   4.9392E+10  -2.8297E+09   1.0221E+11  -2.5726E+08   1.7151E+09   0.0000E+00   0.0000E+00    0.0000E+00    0.0000E+00 th2

Q3   0.0000E+00   0.0000E+00  -2.5726E+07  -2.5726E+08   9.8914E+07  -3.7696E+07  -7.3188E+07   2.1956E+08    0.0000E+00    0.0000E+00 q3

M3   0.0000E+00   0.0000E+00   2.5726E+08   1.7151E+09  -3.7696E+07   4.3084E+09  -2.1956E+08   4.3913E+08    0.0000E+00    0.0000E+00 th3

Q4   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00  -7.3188E+07  -2.1956E+08   2.3775E+08  -1.3728E+08  -1.64561E+08   8.22804E+07 q4

M4   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   2.1956E+08   4.3913E+08  -1.3728E+08   9.3311E+08  -8.22804E+07   2.74268E+07 th4

Q5   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00  -1.64561E+08 -8.22804E+07   1.64561E+08  -8.22804E+07 q5

M5   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   8.22804E+07  2.74268E+07  -8.22804E+07   5.48536E+07 th5
```

```
KNOWN VALUES:                                               # OF SYSTEM BLOCKS =              15
Q1 =                                          -1000 lbs

M1 = Q1*(L1+L2+L3+L4) =                      -75000 IN*LBS

Q2 = M2 = Q3 = M3 = M4 = Q4 = M5                  0

Q5 =                                           1000 lbs

q1 = th1=                          0
----------------------------------------------------------------------------------------------

SOLVED UNKNOWNS:

q2=  0.0000573372 in

th2  0.0000020651 rad

                                                                   -B1            -B2
q3   0.0003357536 in                                           -3006.3287622  -48834.190475

th3  0.0000218994 rad


 q4   0.0005354071 in                                           -30379.296282  -99944.020772

 th4  0.0000401073 rad


 q5   0.0005398215 in                                           -92407.123584  -47253.569633

 th5   0.000076568 rad

 K (BEND HORIZ) FOR 1 SIDE BLOCK =  1867737.5583 lbs/in          1867.7375583 KIPS/IN
 ---------------------------------------------------------------------------------------------

 K (BEND HORIZ) ALL SIDE BLOCKS =  28016063.374 lbs/in           28016.063374 KIPS/IN
 ---------------------------------------------------------------------------------------------
==============================================================================================


TOTAL SIDE BLOCK HORIZONTAL STIFFNESS COEFFICIENT CALCULATION:
SYSTEM 30 E1
----------------------------------------------------------------------------------------------

Khs (SIDEBLOCK HORIZONTAL STIFFNESS) = P/(BENDING DISPL + SHEAR DISPLACEMENT)

Khs       =                   63.53 KIPS/IN        (PER BLOCK)

Khs       =                  952.96 KIPS/IN        (ENTIRE SIDE BLOCK SYSTEM)
----------------------------------------------------------------------------------------------
```

APPENDIX 3

1. System 1-11 Stiffness Table
2. XEL, QD, KU, and KD Values for Bilinear Douglas Fir Caps
3. BASIC Bilinear Stiffness Program Listing
4. "3DOFRUB" System 1 Output File
5. "3DOFRUB" System 1 Input Data File

System 1-11 Stiffness Table

TOTAL KEEL AND SIDE PIER STIFFNESS KIPS/IN
BILINEAR SYSTEMS (1-11) PER DOCKING DRAWINGS

SYSTEM	KVK	KVS	KVSP	KHK	KKHP	KHS	KSHP
1	46808.74	10113.39	4025.64	59223.08	38434.86	5825.13	2212.17
2	46808.74	5231.06	2082.23	59223.08	38434.86	3013.00	1144.23
3	31919.89	6178.56	3211.52	28875.45	22849.71	4055.29	1897.66
4	31919.89	3195.81	1661.13	28875.45	22849.71	2097.56	981.55
5	46808.74	3195.81	1661.13	59223.08	38434.86	2097.56	981.55
6	83270.20	43011.07	22269.52	79683.44	53718.39	28797.14	13345.17
7	83270.20	28512.95	14762.94	79683.44	53718.39	19090.24	8846.80
8	83270.20	21747.17	11259.87	79683.44	53718.39	14560.35	6747.56
9	24375.19	8629.57	4065.53	22050.35	17448.87	5842.63	2409.17
10	19442.11	6808.09	3188.10	17587.78	13917.55	4625.36	1890.63
11	19442.11	5236.99	2452.39	17587.78	13917.55	3557.97	1454.33

QD VALUES:

1 = KEEL HORIZONTAL STIFFNESS
2 = SIDE BLOCK HORIZONTAL STIFFNESS
3 = SIDE BLOCK VERTICAL STIFFNESS

XEL, QD, KU, and KD Values for Bilinear Douglas Fir Caps

SYSTEM #	KEEL CONT. AREA (IN^2)	SHEAR DF PROP LIMI (PSI)	KHK (KIPS/IN)	XEL1 (IN)	KU1-KD1 (KIPS/IN)	QD1 (KIPS)	SB CAP AREA (IN^2)	SHEAR DF PROP LIMI (PSI)	KHS (KIPS/IN)	XEL2 (IN)	KU2-KD2 (KIPS/IN)	QD2 (KIPS)	CAPAREA (IN^2)	D.FIR PROP LIMI (PSI)	KVS (KIPS/IN)	YEL1 (IN)	KU3-KD3 (KIPS/IN)	QD3 (KIPS)	
1	55440.00	930.0	59223.1	0.8706	20788.22	18098.07	8352.00	930.0	5825.13	1.3334	3612.96	4817.602	8352.00	450.0	10113.39	0.3716	6087.75	2262.366	1
2	55440.00	930.0	59223.1	0.8706	20788.22	18098.07	4320.00	930.0	3013.00	1.3334	1868.77	2491.858	4320.00	450.0	5231.06	0.3716	3148.83	1170.188	2
3	55440.00	930.0	28875.5	1.7856	6025.74	10759.39	8352.00	930.0	4055.29	1.9154	2157.63	4132.648	8352.00	450.0	6178.56	0.6083	2967.04	1804.841	3
4	55440.00	930.0	28875.5	1.7856	6025.74	10759.39	5220.00	930.0	2097.56	2.3144	1116.01	2582.897	5220.00	450.0	3195.81	0.7350	1534.68	1128.028	4
5	55440.00	930.0	59223.1	0.8706	20788.22	18098.07	5220.00	930.0	2097.56	2.3144	1116.01	2582.897	5220.00	450.0	3195.81	0.7350	1534.68	1128.028	5
6	108864.00	930.0	79683.4	1.2706	25965.05	32990.45	57672.00	930.0	28797.14	1.8625	15451.97	28779.44	57672.00	450.0	43011.07	0.6034	20741.55	12515.21	6
7	108864.00	930.0	79683.4	1.2706	25965.05	32990.45	38232.00	930.0	19090.24	1.8625	10243.44	19078.50	38232.00	450.0	28512.95	0.6034	13750.01	8296.604	7
8	108864.00	930.0	79683.4	1.2706	25965.05	32990.45	29160.00	930.0	14560.35	1.8625	7812.79	14551.40	29160.00	450.0	21747.17	0.6034	10487.3	6327.919	8
9	42336.00	930.0	22050.4	1.7856	4601.48	8216.272	9600.00	930.0	5842.63	1.5281	3433.46	5246.598	9600.00	450.0	8629.57	0.5006	4564.04	2284.778	9
10	33768.00	930.0	17587.8	1.7856	3670.23	6553.458	7488.00	930.0	4625.36	1.5056	2734.73	4117.349	7488.00	450.0	6808.09	0.4949	3619.99	1791.679	10
11	33768.00	930.0	17587.8	1.7856	3670.23	6553.458	5760.00	930.0	3557.97	1.5056	2103.64	3167.193	5760.00	450.0	5236.99	0.4949	2784.6	1378.212	11

BASIC Bilinear Stiffness Program Listing . . . .

```
10 SCREEN 0: WIDTH 80
20 CLS
30 PRINT "************************************************************************
40 '
50 PRINT:PRINT "              ****SHIP DRYDOCK BLOCKING SYSTEM***       "
60 PRINT:PRINT "  ****TRANSVERSE RESPONSE ASSUMING BILINEAR BEHAVIOR****
70 PRINT:PRINT "  ****USING TIME AND ACCELERATION INPUT DATA****":PRINT
80 '
90 PRINT "************************************************************************
100 '
110 '                      *INITIALIZATION*
120 '
130 DIM F(4001),UDP(4001)
140 C$=" ###.### ####.#####"
150 A$=" ###.### ########.##"
160 D$="######.### #######.#### #######.#### #######.#### ######.#### "
170 PRINT "    ***DATA FILE INFORMATION***" :PRINT
180 PRINT " 1. PREPARE NEW DATA FILE":PRINT
190 PRINT " 2. MODIFY EXISTING DATA FILE":PRINT
200 PRINT " 3. USE EXISTING DATA FILE":PRINT
210 INPUT "         SELECT NUMBER";NN
220 PRINT: INPUT "   DRIVE USED FOR DATA FILES (A:,B:,C:,D:,E:,F:):";ABC$
230 INPUT "              FILE NAME ( OMIT DRIVE LETTER )";F4$
240 F4$=ABC$+F4$
250 INPUT "  DOES YOUR COMPUTER HAVE A GRAPHICS BOARD (Y/N)  "; GR$
260 CLS
270 ON NN GOTO 290,370,460
280 '
290 GOSUB 580:' CALL SUBROUTINE "INPUT DATA"
300 GOSUB 890:' CALL SUBROUTINE "PRINT DATA"
310 GOSUB 1090:' CALL SUBROUTINE "STORE DATA"
320 GOSUB 1220:' CALL SUBROUTINE "CALCULATE RESPONSE"
330 IF GR$="N" OR GR$="n" THEN GOTO 520
340 GOSUB 5310: 'CALL SUBROUTINE "PLOT"
350 GOTO 510
360 '
370 GOSUB 4960:' CALL SUBROUTINE "RECALL DATA"
380 GOSUB 5060:' CALL SUBROUTINE "MODIFY DATA"
390 GOSUB 890 :' CALL SUBROUTINE "PRINT DATA"
400 GOSUB 1090 :' CALL SUBROUTINE "STORE DATA"
410 GOSUB 1220 :' CALL SUBROUTINE "CALCULATE RESPONSE"
420 IF GR$="N" OR GR$="n" THEN GOTO 520
430 GOSUB 5310: 'CALL SUBROUTINE "PLOT"
440 GOTO 510
450 '
460 GOSUB 4960:' CALL SUBROUTINE "RECALL DATA"
470 GOSUB 890 :' CALL SUBROUTINE "PRINT DATA"
480 GOSUB 1220 :' CALL SUBROUTINE "CALCULATE RESPONSE"
490 IF GR$="N" OR GR$="n" THEN GOTO 520
500 GOSUB 5310: 'CALL SUBROUTINE "PLOT"
510 LOCATE 23,2
520 PRINT "PRESS ANY KEY TO":PRINT "RETURN TO THE BILINEAR PROGRAM"
530 A$=INKEY$ : IF A$="" THEN 530
540 CHAIN ABC$+"BILINEAR  ",10
550 END
560 '***************************************************************************
570 '
580 CLS:' SUROUTINE "INPUT DATA"
590 PRINT "      INPUT THE FOLLOWING DATA:":PRINT
600 INPUT "SHIP/SUB BLOCKING SYSTEM: ";SHIP$
610 INPUT "EARTHQUAKE ACCELERATION USED: ";QUAK$
620 INPUT " NUMBER OF POINTS DEFINING THE EXCITATION          NE=";NE
630 INPUT " MASS  (KIPS/IN/S^2)                                M=";M
640 INPUT " SPRING CONSTANT 1  (KIPS/IN)                      KU=";KU
650 INPUT " SPRING CONSTANT 2  (KIPS/IN)                      KD=";KD
660 INPUT "DAMPING COEFFICIENT                                 C=";C
```

```
660 INPUT " DAMPING COEFFICIENT                                    C=";C
670 INPUT "TIME STEP INTEGRATION  (SEC)                            H=";H
680 INPUT " RESTORING FORCE AT 0 DEFLECT & POS. VELOCITY(KIPS)QD=";QD
690 INPUT " PROPORTIONAL LIMIT (KIPS/IN^2)                         P=";P
700 INPUT " AREA OF APPLIED FORCE (IN^2)                           A=";A
710 G=0
720 INPUT "X DISPLACEMENT PLOTTING MAX AMPLITUDE (IN) :";DD
730 INPUT "MAXIMUM RUN TIME OF EARTHQUAKE ACCELERATION INPUT: ";TT
740  INPUT " ARE THE ABOVE VALUES CORRECT  Y/N";YN$
750  IF YN$="N" THEN GOTO 260
760 CLS :PRINT
770 PRINT:PRINT
780 INPUT " INPUT THE NAME OF ACCELERATION DATA FILE YOU WISH TO USE: ",ACCE$
790 OPEN ACCE$ FOR INPUT AS #1
800 PRINT " ACCELERATION FILE BEING READ ... "
810 FOR I=1 TO NE
820 INPUT #1,F(I)
830 NEXT I
840 CLOSE #1
850 PRINT " ACCELERATION DATA FILE INPUT COMPLETE "
860 RETURN
870 '*************************************************************************
880 '
890 CLS: 'SUBROUTINE "PRINT DATA"
900 PRINT:PRINT "       ***SHIP/SUB DRYDOCK BLOCKING SYSTEM***  DATA FILE: ";F4$
910 PRINT:PRINT "              ***RESPONSE FOR BILINEAR BEHAVIOR***":PRINT
920 PRINT "      INPUT DATA:":PRINT
930 PRINT " SHIP/SUB DRYDOCK BLOCKING SYSTEM: ",SHIP$
940 PRINT " EARTHQUAKE ACCELERATION TIME HISTORY USED: ";QUAK$
950 PRINT " NUMBER OF POINTS DEFINING THE EXCITATION NE=";NE
960 PRINT " MASS (KIPS/IN/S^2)                           M=";M
970 PRINT " SPRING CONSTANT 1 (KIPS)                    KU=";KU
980 PRINT " SPRINT CONSTANT 2 (KIPS)                    KD=";KD
990 PRINT " DAMPING COEFFICIENT                          C=";C
1000 PRINT " TIME STEP INTEGRATION (SEC)                 H=";H
1010 PRINT " REST. FORCE AT 0 DEFL. W/POS. VEL (KIPS) QD=";QD
1020 PRINT " HORIZONTAL CONTACT AREA (IN^2)              A=";A
1030 PRINT " SPRING PROPORTIONAL LIMIT (KIPS/IN^2)       P=";P
1040 PRINT " THE DISPLACEMENT PLOT UPPER LIMIT (IN)  DD=";DD
1050 PRINT " THE RUN TIME LIMIT (SEC)                TT=";TT
1060 RETURN
1070 '************************************************************************
1080 '
1090 'SUBROUTINE "STORE DATA"
1100 IF NN<>2 THEN 1130
1110 INPUT " INPUT THE NAME OF THE MODIFIED DATA FILE: ",MD$
1120 F4$=ABC$+MD$
1130 OPEN F4$ FOR OUTPUT AS #1
1140 WRITE #1,SHIP$,QUAK$,NE,M,KU,KD,C,H,QD,P,A,DD,TT
1150 FOR I=1 TO NE
1160 WRITE #1,F(I)
1170 NEXT I
1180 CLOSE #1
1190 RETURN
1200 '************************************************************************
1210 '
1220 'SUBROUTINE "CALCULATE RESPONSE"
1230 '
1240 '                          *INITIALIZATION*
1250 '
1260 'UD = TRANSVERSE RELATIVE SHIP CG DISPLACEMENT WITH DRY DOCK BOTTOM
1270 'UV = TRANSVERSE RELATIVE SHIP CG VELOCITY WITH DRY DOCK BOTTOM
1280 'UA = TRANSVERSE RELATIVE SHIP CG ACCELERATION WITH DRY DOCK BOTTOM
1290 '
1300 '
1310 UD=0 :UV=0 :UA=F(1)/M
1320 F(0)=0
```

```
1330 '
1340 ' [illegible]
1350 '
1360 'THE TOTAL NUMBER OF DATA POINTS = NE [illegible]
1370 '
1380 '
1390 NT=NE
1400 N1T=NT+1
1410 ANN=0
1420 NM1=NT-1
1430 '
1440 '
1450 'A1,A2,A3,A4 ARE COEFFICIENTS FOR THIS FORM OF NUMERICAL SOLUTION
1460 '
1470 '
1480 A1=3/H :A2=6/H :A3=H/2 :A4=6/H^2
1490 '
1500 '
1510 'XEL IS THE ELASTIC LIMIT (PROPORTIONAL LIMIT) FOR THE BLOCKING
1520 'SYSTEM IN INCHES.
1530 '
1540 '
1550 XEL=P*A/KU
1560 '
1570 '
1580 'KY IS A LOCATOR.
1590 '
1600 'WITH BILINEAR BEHAVIOR THERE ARE 5 POSSIBLE LINES THE RESISTANCE
1610 'VERSUS DISPLACEMENT RESPONSE CAN BE ON AS FOLLOWS:
1620 '
1630 'THE INITIAL SLOPE BEFORE ANY PLASTIC DEFORMATION,
1640 'THE TOP PLASTIC LINE,
1650 'THE RIGHT ELASTIC LINE,
1660 'THE BOTTOM PLASTIC LINE,
1670 'THE LEFT ELASTIC LINE,
1680 '
1690 'KY=0 INDICATES THAT THE RESPONSE IS STILL IN THE INITIAL
1700 'ELASTIC REGION AND HAS YET TO GO PLASTIC.
1710 '
1720 'KY=1 INDICATES THAT THE RESPONSE IS NOW ON THE TOP PLASTIC
1730 'LINE OR THE RIGHT ELASTIC LINE.
1740 '
1750 'KY=-1 INDICATES THAT THE RESPONSE IS NOW ON THE BOTTOM PLASTIC
1760 'LINE OR THE LEFT ELASTIC LINE.
1770 '
1780 '
1790 KY=0
1800 '
1810 '
1820 'PK IS THE CURRENT HORIZONTAL STIFFNESS AT TIME T
1830 '
1840 '
1850 PK=KU
1860 '
1870 '
1880 'XMAX IS THE HORIZONTAL DISPLACEMENT AT THE POINT VELOCITY
1890 'GOES FROM POSITIVE TO NEGATIVE AND SHIFTS FROM THE TOP
1900 'PLASTIC LINE TO THE RIGHT ELASTIC LINE.
1910 '
1920 'XMIN IS THE HORIZONTAL DISPLACEMENT AT THE POINT VELOCITY
1930 'GOES FROM NEGATIVE TO POSITIVE AND SHIFTS FROM THE BOTTOM
1940 'PLASTIC LINE TO THE LEFT ELASTIC LINE.
1950 '
1960 'THESE VALUES ARE INTIALLY SET TO ZERO
1970 '
1980 '
```

```
2000 XMAX=0
2010 '
2020 '
2030 T$="TIME-DISPLACEMENT RESPONSE"
2040  II=1
2050 '
2060 '
2070 '
2080 'AN OUTPUT FILE IS NOW CREATED.  THIS INCLUDES TIME, DISPLACEMENT,
2090 'VELOCITY, ACCELERATION, AND RESISTANCE OF THE SHIP IN THE
2100 'TRANSVERSE (HORIZONTAL) DIRECTION RELATIVE TO THE BOTTOM OF
2110 'THE DOCK.  RESISTANCE IS THE RESISTANCE AGAINST DEFORMATION AND IS
2120 'DEPENDANT ON THE LOCATION ON THE RESISTANCE VERSUS DISPL. PLOT.
2130 '
2140 '
2150 PRINT:PRINT:PRINT
2160 INPUT " INPUT NAME OF OUTPUT FILE: ",ACNEW$
2170 OPEN ACNEW$ FOR OUTPUT AS #2
2180 PRINT "WAIT!!! OUTPUT FILE BEING CREATED -----  "
2190 T=0
2200 '
2210 '
2220 'RR IS THE VALUE FOR RESISTANCE AT TIME T (INITIALLY SET AT 0)
2230 '
2240 '
2250 RR=0
2260 '
2270 '
2280 'INITIAL VALUES ARE WRITTEN TO THE FILE BEFORE THE LOOP STARTS:
2290 '
2300 WRITE #2,T,UD,UV,UA,RR
2310 '
2320 '
2330 'ZY,ZZ,WY,WZ ARE LOCATORS SET TO ZERO HERE.  THEY WILL BE
2340 'DESCRIBED WHEN THEY ARE USED LATER.
2350 '
2360 ZY=0
2370 ZZ=0
2380 WY=0
2390 WZ=0
2400 '
2410 '
2420 'THE BEGINNING OF THE NUMERICAL SOLUTION LOOP:
2430 '
2440 '
2450 FOR L=1 TO NT
2460 '
2470 '
2480 'TIME T = THE TIME STEP TIME THE LOOP #
2490 '
2500 T=H*L
2510 '
2520 'BK IS THE CURRENT EFFECTIVE STIFFNESS
2530 '
2540 BK=PK+A4*M+A1*C
2550 '
2560 'DFB IS THE DIFFERENTIAL FORCE AT TIME T
2570 '
2580 DFB=(F(L+1)-F(L))*M+(A2*M+3*C)*UV+(3*M+A3*C)*UA
2590 '
2600 'DUD IS THE DIFFERENTIAL DISPLACEMENT WHICH IS THE
2610 'DIFFERENTIAL FORCE DIVIDED BY THE CURRENT EFFECTIVE STIFFNESS.
2620 '
2630 DUD=DFB/BK
2640 '
```

```
2660 '
2670 DVU=3*DUD/H-3*UV-UA*H/2
2680 '
2690 'THE NEW UD IS THE PREVIOUS DISPLACEMENT PLUS THE DIFFERENTIAL
2700 'DISPLACEMENT.
2710 '
2720 UD=UD+DUD
2730 '
2740 'THE NEW UV IS THE PREVIOUS VELOCITY PLUS THE DIFFERENTIAL
2750 'VELOCITY.
2760 '
2770 UV=UV+DVU
2780 '
2790 '
2800 '
2810 '****************************************************************
2820 '
2830 'THIS IS WHERE THE LOGIC OF HOW THE RESPONSE WORKS AROUND
2840 'THE RESISTANCE VERSUS DISPLACEMENT PLOT BEGINS*****
2850 '
2860 '****************************************************************
2870 '
2880 '
2890 'THE FIRST THING TO CHECK IS WHETHER OR NOT THE RESPONSE IS
2900 'STILL ON THE INITIAL ELASTIC LINE.  IF NO PLASTIC DEFORMATION
2910 'HAS OCCURRED THEN KY=0.  THE SLOPE OF THE RESISTANCE VERSUS
2920 'DISPLACEMENT CURVE SHOULD BE "KU" GOING THROUGH THE ORIGIN.
2930 '
2940 '
2950 IF KY<0 THEN 4040
2960 IF KY>0 THEN 3480
2970 RR=KU*UD
2980 PK=KU
2990 '
3000 '
3010 'THE NEXT CHECK IS TO SEE IF THE RESPONSE HAS GONE PLASTIC.
3020 'IF THIS OCCURS, USING BILINEAR BEHAVIOR, THE NEW RESISTANCE
3030 'VERSUS DISPLACEMENT CURVE WILL HAVE A SLOPE OF KD WITH A
3040 'RR INTERCEPT OF EITHER PLUS QD OR MINUS QD.  QD IS AN INPUT
3050 'AND IS MATERIAL DEPENDENT.
3060 '
3070 '
3080 'IF THE DISPLACEMENT IS LESS THAN -XEL OR MORE THAN +XEL
3090 'THEN THE RESPONSE HAS GONE PLASTIC.
3100 'IF NOT, THE LOOP IS COMPLETED AND OUTPUTS FOR TIME T ARE WRITTEN
3110 'TO THE OUTPUT FILE.
3120 '
3130 IF UD>-XEL AND UD<XEL THEN GOTO 4720
3140 '
3150 'IF THE LOOP GOES HERE IT MEANS THAT THE RESPONSE IS NOW PLASTIC
3160 'ON THE TOP OR BOTTOM PLASTIC LINE.
3170 '
3180 IF UD<-XEL THEN GOTO 4040
3190 '
3200 'IF THE LOOP GOES HERE THEN THE RESPONSE IS ON THE TOP PLASTIC LINE.
3210 '
3220 KY=1
3230 PK=KD
3240 RR=KD*UD+QD
3250 '
3260 'WWW,YYY,ZZ ARE LOCATORS IN  THE LOGIC.  IT IDENTIFIES THE
3270 'RESPONSE SO IT KNOWS IT IS ON THE TOP PLASTIC LINE. AT THIS
3280 'POINT ALL OF THESE VALUES ARE SET TO ZERO.
3290 '
3300 WWW=0
3310 YYY=0
```

```
3320 ZZ=0
3330 '
3340 'THE LOOP IS COMPLETED AT THIS POINT AND THE OUTPUT IS WRITTEN
3350 'TO THE OUTPUT FILE.
3360 '
3370 GOTO 4720
3380 '
3390 '
3400 'THE LOGIC NOW SEES A KY=+1.  ON THE NEXT LOOP THE LOGIC WILL
3410 'DO A VELOCITY CHECK.  THAT IS THE NEXT STEP HERE.  IF THE VELOCITY
3420 'SHIFTS FROM POSITIVE TO NEGATIVE THE RESPONSE SHIFTS FROM THE
3430 'TOP PLASTIC LINE TO THE RIGHT ELASTIC LINE.
3440 '
3450 'IF THE VELOCITY DID NOT GO NEGATIVE THEN THE LOOP RETURNS TO
3460 'THE TOP PLASTIC LINE EQUATION.
3470 '
3480 IF UV>0 THEN GOTO 3720
3490 '
3500 'IF THE RESPONSE JUST CAME FROM THE TOP PLASTIC LINE YYY=0.
3510 'OTHERWISE IT IS ALREADY ON THE RIGHT ELASTIC LINE.  THIS YYY
3520 'CHECK IS USED TO DETERMINE THE VALUE OF XMAX.  WHICH IS THE
3530 'THE MAXIMUM HORIZONTAL POSITIVE DISPLACEMENT WHEN THE VELOCITY
3540 'SHIFTS FROM POSITIVE TO NEGATIVE.
3550 '
3560 IF YYY>0 THEN GOTO 3630
3570 '
3580 'IF THE SHIFT FROM THE PLASTIC LINE TO THE ELASTIC LINE JUST OCCURRED,
3590 'THEN XMAX IS ASSIGNED THE VALUE OF THE CURRENT DISPLACEMENT.
3600 'OTHERWISE XMAX WILL RETAIN THE VALUE OF THE PREVIOUS MAXIMUM VALUE.
3610 '
3620 ZZ=UD
3630 YYY=1
3640 XMAX=ZZ
3650 '
3660 'THE NEXT CHECK IS TO DETERMINE WHEN THE RIGHT ELASTIC LINE SHIFTS
3670 'TO THE LOWER PLASTIC LINE.  THIS OCCURS WHEN DISPLACEMENT
3680 'DECREASES TO THE POINT IT BECOMES LESS THAN THE XMAX VALUE BY
3690 'TWO TIMES THE VALUE OF XEL.  THIS VALUE WAS DERIVED AND WAS
3700 'VERIFIED IN BIGGS BOOK ON STRUCTURAL DYNAMICS (1964).
3710 '
3720 IF UD<(XMAX-2*XEL) THEN GOTO 4040
3730 '
3740 'THE NEXT CHECK IS TO SEE IF THE RESPONSE SHIFTS BACK TO THE TOP
3750 'PLASTIC LINE IF THE VELOCITY SHIFTED WHILE STILL ON THE RIGHT
3760 'ELASTIC LINE AND WENT BACK UP THE LINE AND EXCEEDED THE VALUE
3770 'OF XMAX.
3780 '
3790 IF UD>XMAX THEN GOTO 3220
3800 '
3810 'THIS NEXT CHECK IS A LOCATOR.  IF YYY=0 THEN THE LOGIC RETURNS
3820 'THE LOOP TO THE TOP PLASTIC LINE.
3830 '
3840 IF YYY=0 THEN GOTO 3220
3850 '
3860 'IF YYY IS NOT ZERO THEN THE LOGIC SEES THE RESPONSE AS ON THE
3870 'RIGHT ELASTIC LINE.  IT ASSIGNS THE RESPONSE AGAIN TO KY=1.
3880 'ALL THE EQUATIONS OF "RR= " ARE THE VALUES OF THE RESISTANCE
3890 'AT THAT POINT ALONG THE RESPONSE PLOT.
3900 '
3910 KY=1
3920 PK=KU
3930 RR=KU*UD+(KD-KU)*XMAX+QD
3940 '
3950 'THE LOOP IS AGAIN ENDED AND THE OUTPUT RECORDED.
3960 '
3970 GOTO 4720
```

```
3980 '
3990 '
4000 'THIS NEXT CHECK WAS ARRIVED AT WHEN THE DISPLACEMENT WAS LESS
4010 'THAN XMAX MINUS TWO TIMES XEL.  IF THE VELOCITY SHIFTS POSITIVE
4020 'HERE A LATER CHECK WILL DETERMINE A VALUE FOR XMIN.
4030 '
4040 IF UV>0 THEN GOTO 4350
4050 '
4060 'THE ONLY WAY WWW=1 IS IF THE RESPONSE WAS LAST ON THE LEFT
4070 'ELASTIC LINE.  THIS CHECK IS IN CASE THE RESPONSE STAYS ELASTIC
4080 'AND STAYED ON THE SAME LINE.
4090 '
4100 IF WWW=1 THEN GOTO 4350
4110 '
4120 'THE LOGIC NOW SEES THE RESPONSE AS ON THE BOTTOM PLASTIC LINE.
4130 'KY NOW BECOMES KY=-1.
4140 '
4150 KY=-1
4160 PK=KD
4170 RR=KD*UD-QD
4180 '
4190 'UUU AND WZ ARE SET TO ZERO TO IDENTIFY THE RESPONSE AS BEING
4200 'CURRENTLY ON THE BOTTOM PLASTIC LINE.
4210 '
4220 UUU=0
4230 WZ=0
4240 '
4250 'THE LOOP IS ENDED HERE AND THE OUTPUT RECORDED.
4260 '
4270 GOTO 4720
4280 '
4290 '
4300 'IF UUU IS NOW FOUND TO BE GREATER THAN ZERO, THE LOGIC KNOWS THAT
4310 'THAT THE RESPONSE IS ALREADY ON THE LEFT ELASTIC LINE AND XMIN
4320 'HAS ALREADY BEEN ASSIGNED A VALUE. IF UUU=0 THEN THE CURRENT
4330 'VALUE OF UD IS ASSIGNED TO XMIN.
4340 '
4350 IF UUU>0 THEN GOTO 4370
4360 WZ=UD
4370 UUU=1
4380 XMIN=WZ
4390 '
4400 'NOW WITH THE VALUE OF XMIN KNOWN THE VALUE OF DISPLACEMENT IS
4410 'CHECKED AGAINST THE UPPER LIMIT OF THE ELASTIC LINE WHICH IS
4420 'XMIN PLUS TWO TIMES XEL.  IF IT IS GREATER THAN THE LOOP RETURNS
4430 'TO THE TOP PLASTIC LINE.
4440 '
4450 IF UD>(XMIN+2*XEL) THEN GOTO 3220
4460 '
4470 'IF THE VALUE OF UD IS LESS THAN XMIN THAT MEANS THAT THE VELOCITY
4480 'SHIFTED BACK TO NEGATIVE WHILE ON THE LEFT ELASTIC LINE.
4490 'ONCE IT GOES LESS THAN XMIN THAT THE RESPONSE SHIFTS TO THE BOTTOM
4500 'LINE AGAIN.
4510 '
4520 IF UD<XMIN THEN GOTO 4150
4530 '
4540 'THE LOGIC NOW RECOGNIZES THAT THE RESPONSE IS ON THE LEFT ELASTIC
4550 'LINE.  WWW=1 IS A LOCATOR FOR THIS LINE.
4560 WWW=1
4570 RR=KU*UD+(KD-KU)*XMIN-QD
4580 PK=KU
4590 '
4600 'THE LOOP IS COMPLETE AND THE OUTPUT VALUES ARE RECORDED.
4610 '
4620 GOTO 4720
4630 '
```

```
4650 '
4660 '*****************************************************************
4670 '
4680 'NOW ACCELERATION IS CALCULATED FOR THE APPROPRIATE POINT ON THE
4690 'RESISTANCE VERSUS DISPLACEMENT PLOT, AND THE OUTPUTS ARE
4700 'WRITTEN TO THE OUTPUT FILE.
4710 '
4720 UA=(F(L+1)*M-C*UV-RR)/M
4730 '
4740 WRITE #2,T,UD,UV,UA,RR
4750 '
4760 '*******************************************************************
4770 '
4780 'UDP(L) ARE THE VALUES OF DISPLACEMENT AT EACH TIME T WHICH IS USED
4790 'IN THIS PROGRAMS PLOTTING ROUTINE.
4800 '
4810 UDP(L)=UD
4820 '
4830 'END OF THE LOOP*****
4840 '
4850 NEXT L
4860 CLOSE #2
4870 '
4880 '
4890 '
4900 PRINT "       PRESS ANY KEY TO CONTINUE"
4910 A$=INKEY$ : IF A$="" THEN 4910
4920 RETURN
4930 '**********************************************************************
4940 '***********************************************************************
4950 '
4960 CLS: 'SUBROUTINE "RECALL DATA"
4970 PRINT "WAIT!!!! INPUTING PREVIOUS DATA FILE ----- "
4980 OPEN F4$ FOR INPUT AS #1
4990 INPUT #1,SHIP$,QUAK$,NE,M,KU,KD,C,H,QD,P,A,DD,TT
5000 FOR I=1 TO NE
5010 INPUT #1,F(I)
5020 NEXT I
5030 CLOSE #1
5040 RETURN
5050 '
5060 CLS: 'SUBROUTINE "MODIFY DATA"
5070 PRINT "NUM POINTS DEFINING THE EXCITATION   NE=";NE
5080 INPUT "NEW VALUE: *NO CHANGE: PRESS ENTER*  NE=";I$:IF I$<>""THEN NE=VAL(I$
)
5090 PRINT "MASS                                  M=";M
5100 INPUT "NEW VALUE: *NO CHANGE PRESS ENTER*  M=";Q$:IF Q$<>""THEN M=VAL(Q$)
5110 PRINT "SPRING CONSTANT 1                    KU =";KU
5120 INPUT "NEW VALUE *NO CHANGE PRESS ENTER*  KU=";Q$:IF Q$<>""THEN KU=VAL(Q$)
5130 PRINT "SPRING CONSTANT 2                    KD =";KD
5140 INPUT "NEW VALUE *NO CHANGE PRESS ENTER*  KD=";Q$:IF Q$<>""THEN KD=VAL(Q$)
5150 PRINT "SPRING CONSTANT 2                    KD =";KD
5160 PRINT "DAMPING COEFFICIENT                   C=";C
5170 INPUT "NEW VALUE *NO CHANGE PRESS ENTER*   C=";Q$:IF Q$<>""THEN C=VAL(Q$)
5180 PRINT "TIME STEP OF INTEGRATION              H=";H
5190 INPUT "NEW VALUE *NO CHANGE PRESS ENTER*   H=";Q$:IF Q$<>""THEN  H=VAL(Q$)
5200 PRINT "RESTORING FORCE               QD=";QD
5210 INPUT "NEW VALUE *NO CHANGE: PRESS ENTER* QD=";Q$:IF Q$<>""THEN QD=VAL(Q$)
5220 PRINT "NEW HORIZONTAL CONTACT AREA           A=";A
5230 INPUT "NEW VALUE *NO CHANGE PRESS ENTER*   A=";Q$:IF Q$<>""THEN A=VAL(Q$)
5240 PRINT "X DISPLACEMENT PLOTTING MAX AMPLITUDE (IN) DD=";DD
5250 INPUT "NEW VALUE *NO CHANGE PRESS ENTER*  DD=";Q$:IF Q$<>""THEN DD=VAL(Q$)
5260 PRINT "MAXIMUM RUN TIME OF EARTHQUAKE (SEC)        TT=";TT
5270 INPUT "NEW VALUE *NO CHANGE PRESS ENTER*  TT=";Q$:IF Q$<>""THEN TT=VAL(Q$)
5280 RETURN
5290 '
```

```
5300 '*****************************************************************************
5310 '
5320 ' SUBROUTINE "PLOT"
5330 CLS :KEY OFF
5340 LOCATE 10,1
5350 PRINT:PRINT:PRINT"TO OBTAIN A PRINT OF THE FOLLOWING GRAPH, SET PRINTER ON
AND PRESS SHIFT-PrtSc"
5360 PRINT "    PRESS ANY KEY TO CONTINUE  "
5370 A$=INKEY$:IF A$="" THEN 5370
5380  SCREEN 1 : COLOR 0,1
5390 WINDOW SCREEN (0,-10)-(30,10)
5400 LINE (4,DD)-(4,-DD),1
5410 LINE (4,0)-(TT+4,0),1
5420 LOCATE 3,4
5430 PRINT "X"
5440 LOCATE 23,30
5450 PRINT "TIME"
5460 T$="TIME-DISPLACEMENT RESPONSE"
5470 LOCATE 2,(40-LEN(T$))/2+1
5480 PRINT T$
5490 LOCATE 3,1
5500 PSET (0,0),2
5510 FOR I=0 TO NE
5520 T=H*I
5530 LINE (T+4,UDP(I))-((T+H)+4,UDP(I+1)),2
5540 NEXT I
5550 RETURN
5560 '*****************************************************************************
```

"3DOFRUB" System 1 Output File. . .

```
                            **** System  1 ****

                              ** Hull 616 **

                          * Ship Parameters *

      Weight          Moment of Inertia          K.G.
  16369.9 kips    2410451.0 kips-in-sec2     193.0 ins


                        * Drydock Parameters *

Side Block Height    Side Block Width    Keel Block Height    Keel Block Width
   74.0 ins              42.0 ins                60.0 ins             48.0 ins

Side-to-Side Pier Distance    Wale Shore Ht.    Wale Shore Stiffness  Cap Angle
      144.0 ins                      .0 ins                .0 kips/in  .377 rad

1Side Side Pier Contact Area    Total Keel Pier Contact Area       kkhp
             8352.0 in2                      55440.0 in2          38434.9 kips/in

B/B Friction Coeff    H/B Friction Coeff      kshp             kvsp
        .430                  .530        2212.2 kips/in  4025.6 kips/in

Side Pier Fail Stress Limit     Keel Pier Fail Stress Limit      QD1
             .700 kips/in2                     .450 kips/in2     18098.1 kips

Side Pier Vertical Stiffness    Side Pier Horizontal Stiffness    QD2
      10113.4 kips/in                  5825.1 kips/in           4817.6 kips

Keel Pier Vertical Stiffness    Keel Pier Horizontal Stiffness    QD3
      46808.7 kips/in                 53223.1 kips/in           2262.4 kips


                   * System Parameters and Inputs *

Earthquake Used is 1940 EL CENTRO

Horizontal acceleration input is HORIZONTAL

Vertical acceleration input is
                         Earthquake Acceleration Time History.

Vertical/Horizontal Ground Acceleration Ratio   Data Time Increment
           1.000                                       .010 sec

Gravitational Constant   % System Damping
      386.09 in/sec2             5.00 %

                         Mass Matrix

       42.3992               .0000            8183.0420
         .0000             42.3992                .0000
     8183.0420               .0000         2410451.0000

                        Damping Matrix

      118.1018               .0000            5027.6454
         .0000            168.5898                .0000
     5027.6454               .0000         1549181.3597
```

```
                    Stiffness Matrix


      70878.3400            .0000     168103.6400
           .0000       67035.5200           .0000
     168103.6400            .0000   [illegible]1610.6070


Undamped Natural Frequencies       Mode #1          Mode #2           Mode #3
                                 6.425 rad/sec  69.650 rad/sec   39.763 rad/sec
Damped Natural Frequencies         Mode #1          Mode #2           Mode #3
                                 6.416 rad/sec  69.563 rad/sec   39.713 rad/sec


For Earthquake Acceleration of 100.00 % of the 1940 EL CENTRO

Maximums/Failures          X (ins)   Y (ins)          Theta (rads)  Time (sec)
-----------------        --------   --------        ------------- -----------
 Maximum X                .209810                                    15.87
 Maximum Y                          -.197584                          8.01
 Maximum Rotation                                      -.049156      13.83
Side block sliding        .003405    .012522           -.001452       5.27
Keel block sliding       -.087698   -.003059           -.014561       6.32
Side block overturning    .010854    .042672           -.002285       5.26
Keel block overturning    .020383    .052877            .001717       4.71
Side block liftoff       -.007883   -.103857           -.003915       4.96
Side block crushing      -.018756   -.008475            .008794       5.47


For Earthquake Acceleration of  90.00 % of the 1940 EL CENTRO

Maximums/Failures          X (ins)   Y (ins)          Theta (rads)  Time (sec)
-----------------        --------   --------        ------------- -----------
 Maximum X               -.215308                                    13.89
 Maximum Y                          -.185858                          8.01
 Maximum Rotation                                      -.049429      13.84
Side block sliding       -.011928   -.025677           -.000336       5.28
Keel block sliding        .064047    .139538            .019749       7.91
Side block overturning   -.011928   -.025677           -.000336       5.28
Keel block overturning   -.031319   -.030563            .001947       4.75
Side block liftoff       -.001316   -.079103           -.003906       4.97
Side block crushing      -.011383   -.016669            .008267       5.48


For Earthquake Acceleration of  80.00 % of the 1940 EL CENTRO

Maximums/Failures          X (ins)   Y (ins)          Theta (rads)  Time (sec)
-----------------        --------   --------        ------------- -----------
 Maximum X                .230242                                    17.20
 Maximum Y                          -.164004                          8.01
 Maximum Rotation                                       .048575      19.79
Side block sliding       -.004720   -.030771            .001913       5.78
Keel block sliding        .060451    .124985            .019718       7.91
Side block overturning   -.004720   -.030771            .001913       5.78
Keel block overturning   -.022077    .057476           -.005186       5.03
Side block liftoff        .001802   -.049706           -.003757       4.98
Side block crushing      -.011827   -.010554            .008424       5.48
```

```
For Earthquake Acceleration of  30.00 % of the 1940 EL CENTRO

Maximums/Failures          X (ins)    Y (ins)         Theta (rads)  Time (sec)
-----------------         --------   --------        ------------- -----------
 Maximum X                -.022720                                   8.06
 Maximum Y                           -.042209                        8.00
 Maximum Rotation                                     .005146        7.49
Side block sliding         .008838    .009183        -.000124        7.24
Side block overturning     .008838    .009183        -.000124        7.24
Side block liftoff         .014493    .007288         .002863        5.52


For Earthquake Acceleration of  20.00 % of the 1940 EL CENTRO

Maximums/Failures          X (ins)    Y (ins)         Theta (rads)  Time (sec)
-----------------         --------   --------        ------------- -----------
 Maximum X                -.016896                                   7.98
 Maximum Y                           -.026873                        4.79
 Maximum Rotation                                     .003483        7.48
Side block liftoff         .006766    .014913         .002418        6.41


For Earthquake Acceleration of  10.00 % of the 1940 EL CENTRO

Maximums/Failures          X (ins)    Y (ins)         Theta (rads)  Time (sec)
-----------------         --------   --------        ------------- -----------
 Maximum X                -.008056                                   7.98
 Maximum Y                           -.013437                        4.79
 Maximum Rotation                                     .001623        7.45

No failures occurred.


For Earthquake Acceleration of  19.00 % of the 1940 EL CENTRO

Maximums/Failures          X (ins)    Y (ins)         Theta (rads)  Time (sec)
-----------------         --------   --------        ------------- -----------
 Maximum X                -.016039                                   7.98
 Maximum Y                           -.025530                        4.79
 Maximum Rotation                                     .003303        7.48
Side block liftoff         .008084    .018012         .002424        6.42


For Earthquake Acceleration of  18.00 % of the 1940 EL CENTRO

Maximums/Failures          X (ins)    Y (ins)         Theta (rads)  Time (sec)
-----------------         --------   --------        ------------- -----------
 Maximum X                -.015300                                   7.98
 Maximum Y                           -.024186                        4.79
 Maximum Rotation                                     .003223        7.48
Side block liftoff         .007658   -.017987         .003007        6.52
```

```
    For Earthquake Acceleration of  17.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)    Y (ins)         Theta (rads)  Time (sec)
-----------------       --------   --------       -------------  ----------
 Maximum X              -.014413                                   7.98
 Maximum Y                         -.022842                        4.79
 Maximum Rotation                                   .003024        7.48
Side block liftoff        .010243    .006283        .002757        6.55


For Earthquake Acceleration of  16.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)    Y (ins)         Theta (rads)  Time (sec)
-----------------       --------   --------       -------------  ----------
 Maximum X              -.013510                                   7.98
 Maximum Y                         -.021499                        4.79
 Maximum Rotation                                   .002799        7.47
Side block liftoff      -.003631    .008820        -.002431        7.87


For Earthquake Acceleration of  15.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)    Y (ins)         Theta (rads)  Time (sec)
-----------------       --------   --------       -------------  ----------
 Maximum X              -.012523                                   7.98
 Maximum Y                         -.020155                        4.79
 Maximum Rotation                                   .002561        7.47

No failures occurred.
```

"3DOFRUB" System 1 Input Data File.

```
16369.[illegible] 193.6 2410[illegible] 10113.59 4025[illegible]64 46008.[illegible] 0[illegible]0
 5825.15 5922[illegible].0[illegible] 2212.17 58434.86 18098.07 4817.60 226[illegible]7 386.09
42.00 48.00 74.00 60.00 0.43 0.53
144.00 0.70 0.45 8352.0 55440.0 0.05
616 1 0.377


LAFAYETTE SSBN 616
NO ISOLATOR ALL BILINEAR
8 SPACING COMPOSITE
NO WALE SHORES
5 % DAMPING
NO SPECIFIC LOCATION
845-2006640
S1KHORIG.WK1 & S1SHORIG.WK1
S1ORBILN.DAT  1532 21 JAN 88
```

APPENDIX 4

1. Rubber Cap Vertical Stiffness Spreadsheets
2. One Inch Rubber Cap Systems Stiffness Table
3. XEL, YEL, QD, KU, and KD Values for Once Inch Rubber Cap Systems
4. "3DOFRUB" System 12 Output File
5. "3DOFRUB" System 12 Input Data File

Rubber Cap Vertical Stiffness Spreadsheets. . . . .

VERTICAL STIFFNESS CALCULATIONS FOR DRYDOCK BLOCKS

HULL TYPE 616 DOCKING PLAN # = 845-2006640

SYSTEM # 12 KEEL BLOCKS ORIGINAL DOCKING DRAWING
RUBBER CAP E1

BLOCK SPA 8.00 FEET

VERTICAL STIFFNESS:

LEVEL #	MATERIAL	E (PSI)	LENGTH (IN) (DEPTH) (B)	WIDTH (IN) (TRANSVERSE) (H)	HEIGHT (IN) (L)	K (KIPS/IN)	1/K	PIER TOTAL K (KIPS/IN)
1	RUBBER	992.00	42.00	24.00	1.00	999.94	0.0010001	459.76
2	D.FUR	12539.19	42.00	24.00	4.00	3159.88	0.0003165	
3	OAK	23980.00	42.00	33.67	29.00	1169.35	0.0008552	
4	CONCRETE	4000000.00	42.00	48.00	27.00	298666.67	0.0000033	
					61.00			
		1945.83						
					# BLOCKS	55		TOTAL STIFF OF BLOCK SY (KIPS/IN):
								25286.68

VERTICAL STIFFNESS CALCULATIONS FOR DRYDOCK BLOCKS

HULL TYPE 616 DOCKING PLAN # = 845-2006640

SYSTEM # 12 KEEL BLOCKS ORIGINAL DOCKING DRAWING
RUBBER CAP E2

BLOCK SPA 8.00 FEET

VERTICAL STIFFNESS:

LEVEL #	MATERIAL	E (PSI)	LENGTH (IN) (DEPTH) (B)	WIDTH (IN) (TRANSVERSE) (H)	HEIGHT (IN) (L)	K (KIPS/IN)	1/K	PIER TOTAL K (KIPS/IN)
1	RUBBER	3571.00	42.00	24.00	1.00	3599.57	0.0002778	688.32
2	D.FUR	12539.19	42.00	24.00	4.00	3159.88	0.0003165	
3	OAK	23980.00	42.00	33.67	29.00	1169.35	0.0008552	
4	CONCRETE	4000000.00	42.00	48.00	27.00	298666.67	0.0000033	
					61.00			
		1845.83						
					# BLOCKS	55		TOTAL STIFF OF BLOCK SY (KIPS/IN):
								37857.79

```
VERTICAL STIFFNESS CALCULATIONS

HULL TYPE   616    DOCKING PLAN # =    845-2006640

SYSTEM #        12            SIDE BLOCKS          ORGINAL DOCKING DRAWING
                                                   RUBBER CAP E1
BLOCK SPACING =         8.00 FEET

VERTICAL STIFFNESS:

----------------------------------------------------------------------------------------------
                                                                                       PIER
 LEVEL  MATERIAL      E       LENGTH     WIDTH      HEIGHT        K           1/K     TOTAL K
   #                (PSI)      (IN)       (IN)       (IN)     (KIPS/IN)               (KIPS/IN)
----------------------------------------------------------------------------------------------
                             (DEPTH)  (TRANSVERSE)
                               (B)        (H)        (L)


   1     RUBBER     992.00    12.00      24.00       1.00      285.70     0.0035002   157.04
   2     D.FIR    12539.19    12.00      24.00       6.00      601.88     0.0016615
   3      OAK     23980.00    23.40      29.70      20.00      833.28     0.0012001
   4    CONCRETE 4000000.00   48.00      42.00      48.00   168000.00     0.0000060
                                                    75.00

                    850.00                          #                             TOTAL STIFF
                                                  BLOCKS           29             OF BLOCK SY
                                                                                  (KIPS/IN):

                                                                                     4554.23
```

```
VERTICAL STIFFNESS CALCULATIONS

HULL TYPE   616    DOCKING PLAN # =    845-2006640

SYSTEM #        12            SIDE BLOCKS          ORGINAL DOCKING DRAWING
                                                   RUBBER CAP E2
BLOCK SPACING =         8.00 FEET

VERTICAL STIFFNESS:

----------------------------------------------------------------------------------------------
                                                                                       PIER
 LEVEL  MATERIAL      E       LENGTH     WIDTH      HEIGHT        K           1/K     TOTAL K
   #                (PSI)      (IN)       (IN)       (IN)     (KIPS/IN)               (KIPS/IN)
----------------------------------------------------------------------------------------------
                             (DEPTH)  (TRANSVERSE)
                               (B)        (H)        (L)


   1     RUBBER    3571.00    12.00      24.00       1.00     1028.45     0.0009723   260.43
   2     D.FIR    12539.19    12.00      24.00       6.00      601.88     0.0016615
   3      OAK     23980.00    23.40      29.70      20.00      833.28     0.0012001
   4    CONCRETE 4000000.00   48.00      42.00      48.00   168000.00     0.0000060
                                                    75.00

                    850.00                          #                             TOTAL STIFF
                                                  BLOCKS           29             OF BLOCK SY
                                                                                  (KIPS/IN):

                                                                                     7552.43
```

TOTAL KEEL AND SIDE PIER STIFFNESS KIPS/IN
STANDARD & RUBBER CAPPED BILINEAR SYSTEMS

SYSTEM	KVK	KVS	KVSP	KHK	KKHP	KHS	KSHP	KVKP
1	46808.74	10113.39	4025.64	59223.08	38434.86	5825.13	2212.17	46808.74
2	46808.74	5231.06	2082.23	59223.08	38434.86	3013.00	1144.23	46808.74
3	31919.89	6178.56	3211.52	28875.45	22849.71	4055.29	1897.66	31919.89
4	31919.89	3195.81	1661.13	28875.45	22849.71	2097.56	981.55	31919.89
5	46808.74	3195.81	1661.13	59223.08	38434.86	2097.56	981.55	46808.74
6	83270.20	43011.07	22269.52	79683.44	53718.39	28797.14	13345.17	83270.2
7	83270.20	28512.95	14762.94	79683.44	53718.39	19090.24	8846.80	83270.2
8	83270.20	21747.17	11259.87	79683.44	53718.39	14560.35	6747.56	83270.2
9	24375.19	8629.57	4065.53	22050.35	17448.87	5842.63	2409.17	24375.19
10	19442.11	6808.09	3188.10	17587.78	13917.55	4625.36	1890.63	19442.11
11	19442.11	5236.99	2452.39	17587.78	13917.55	3557.97	1454.33	19442.11
12	25286.68	4554.23	7552.43	18215.1	18215.1	1842.39	1842.39	37857.79
30	25286.68	2355.63	3906.43	18215.1	18215.1	952.96	952.96	37857.79
31	20197.36	3975.48	6083.7	13704.07	13704.07	1710.14	1710.14	27487.98
32	20197.36	2056.28	3146.74	13704.07	13704.07	884.55	884.55	27487.98
33	25286.68	2056.28	3146.74	18215.1	18215.1	884.55	884.55	37857.79
34	47016.9	25596.13	37814.68	28237.21	28237.21	11392.11	11392.11	68580.41
35	47016.9	16968.22	25068.16	28237.21	28237.21	7552.07	7552.07	68580.41
36	47016.9	12941.87	19119.78	28237.21	28237.21	5760.05	5760.05	68580.41
37	15423.44	5101.21	8319.8	10464.93	10464.93	2089.33	2089.33	20990.82
38	12302.03	3911.02	6310.69	8347.03	8347.03	1622.73	1622.73	16742.68
39	12302.03	3008.48	4854.38	8347.03	8347.03	1248.25	1248.25	16742.68

One Inch Rubber Cap Systems Stiffness Table . . . .

QD VALUES:

1 = KEEL HORIZONTAL STIFFNESS
2 = SIDE BLOCK HORIZONTAL STIFFNESS
3 = SIDE BLOCK VERTICAL STIFFNESS

SYSTEM #	KEEL CONT. AREA (IN^2)	SHEAR DF PROP LIMI (PSI)	KHK (KIPS/IN)	XEL1 (IN)	KU1-KD1 (KIPS/IN)	QD1 (KIPS)	SB CAP AREA (IN^2)	SHEAR DF PROP LIMI (PSI)	KHS (KIPS/IN)	XEL2 (IN)	KU2-KD2 (KIPS/IN)	QD2 (KIPS)
1	55440.00	930.0	59223.1	0.8706	20788.22	18098.07	8352.00	930.0	5825.13	1.3334	3612.96	4817.602
2	55440.00	930.0	59223.1	0.8706	20788.22	18098.07	4320.00	930.0	3013.00	1.3334	1868.77	2491.858
3	55440.00	930.0	28875.5	1.7856	6025.74	10759.39	8352.00	930.0	4055.29	1.9154	2157.63	4132.648
4	55440.00	930.0	28875.5	1.7856	6025.74	10759.39	5220.00	930.0	2097.56	2.3144	1116.01	2582.897
5	55440.00	930.0	59223.1	0.8706	20788.22	18098.07	5220.00	930.0	2097.56	2.3144	1116.01	2582.897
6	108864.00	930.0	79683.4	1.2706	25965.05	32990.45	57672.00	930.0	28797.14	1.8625	15451.97	28779.44
7	108864.00	930.0	79683.4	1.2706	25965.05	32990.45	38232.00	930.0	19090.24	1.8625	10243.44	19078.50
8	108864.00	930.0	79683.4	1.2706	25965.05	32990.45	29160.00	930.0	14560.35	1.8625	7812.79	14551.40
9	42336.00	930.0	22050.4	1.7856	4601.48	8216.272	9600.00	930.0	5842.63	1.5281	3433.46	5246.598
10	33768.00	930.0	17587.8	1.7856	3670.23	6553.458	7488.00	930.0	4625.36	1.5056	2734.73	4117.349
11	33768.00	930.0	17587.8	1.7856	3670.23	6553.458	5760.00	930.0	3557.97	1.5056	2103.64	3167.193
12	55440.00	930.0	18215.1	2.8306	0	0	8352.00	930.0	1842.39	4.2159	0	0
30	55440.00	930.0	18215.1	2.8306	0	0	4320.00	930.0	952.96	4.2159	0	0
31	55440.00	930.0	13704.1	3.7623	0	0	8352.00	930.0	1710.14	4.5419	0	0
32	55440.00	930.0	13704.1	3.7623	0	0	5220.00	930.0	884.55	5.4882	0	0
33	55440.00	930.0	18215.1	2.8306	0	0	5220.00	930.0	884.55	5.4882	0	0
34	108864.00	930.0	28237.2	3.5855	0	0	57672.00	930.0	11392.11	4.7081	0	0
35	108864.00	930.0	28237.2	3.5855	0	0	38232.00	930.0	7552.07	4.7081	0	0
36	108864.00	930.0	28237.2	3.5855	0	0	29160.00	930.0	5760.05	4.7081	0	0
37	42336.00	930.0	10464.9	3.7623	0	0	9600.00	930.0	2089.33	4.2731	0	0
38	33768.00	930.0	8347.0	3.7623	0	0	7488.00	930.0	1622.73	4.2914	0	0
39	33768.00	930.0	8347.0	3.7623	0	0	5760.00	930.0	1248.25	4.2914	0	0

XEL, YEL, QD, KU, and KD Values
for Once Inch Rubber Cap Systems.

s~s	CAPAREA (IN^2)	CAP PROP LIM1 (PSI)	KVS (KIPS/IN)	YEL1 (IN)	KU3-KD3 (KIPS/IN)	QD3 (KIPS)	KEEL AREA (IN^2)	CAP PROP LIM1 (PSI)	KVK (KIPS/IN)	YEL3 (IN)	KU5-KD5 (KIPS/IN)	QD4 (KIPS)
1	8352.00	450.0	10113.39	0.3716	6087.75	2262.366	55440.00	450.0	46808.74	0.5330	0	0
2	4320.00	450.0	5231.06	0.3716	3148.83	1170.188	55440.00	450.0	46808.74	0.5330	0	0
3	8352.00	450.0	6178.56	0.6083	2967.04	1804.841	55440.00	450.0	31919.89	0.7816	0	0
4	5220.00	450.0	3195.81	0.7350	1534.68	1128.028	55440.00	450.0	31919.89	0.7816	0	0
5	5220.00	450.0	3195.81	0.7350	1534.68	1128.028	55440.00	450.0	46808.74	0.5330	0	0
6	57672.00	450.0	43011.07	0.6034	20741.55	12515.21	108864.00	450.0	83270.2	0.5883	0	0
7	38232.00	450.0	28512.95	0.6034	13750.01	8296.604	108864.00	450.0	83270.2	0.5883	0	0
8	29160.00	450.0	21747.17	0.6034	10487.3	6327.919	108864.00	450.0	83270.2	0.5883	0	0
9	9600.00	450.0	8629.57	0.5006	4564.04	2284.778	42336.00	450.0	24375.19	0.7816	0	0
10	7488.00	450.0	6808.09	0.4949	3619.99	1791.679	33768.00	450.0	19442.11	0.7816	0	0
11	5760.00	450.0	5236.99	0.4949	2784.6	1378.212	33768.00	450.0	19442.11	0.7816	0	0
12	8352.00	99.2	4554.23	0.1819	-2998.2	-545.441	55440.00	99.2	25286.68	0.2175	-12571.1	-2734.11
30	4320.00	99.2	2355.63	0.1819	-1550.8	-282.126	55440.00	99.2	25286.68	0.2175	-12571.1	-2734.11
31	8352.00	99.2	3975.48	0.2084	-2108.22	-439.368	55440.00	99.2	20197.36	0.2723	-7290.62	-1985.20
32	5220.00	99.2	2056.28	0.2518	-1090.46	-274.605	55440.00	99.2	20197.36	0.2723	-7290.62	-1985.20
33	5220.00	99.2	2056.28	0.2518	-1090.46	-274.605	55440.00	99.2	25286.68	0.2175	-12571.1	-2734.11
34	57672.00	99.2	25596.13	0.2235	-12218.5	-2731.00	108864.00	99.2	47016.9	0.2297	-21563.5	-4952.92
35	38232.00	99.2	16968.22	0.2235	-8099.94	-1810.44	108864.00	99.2	47016.9	0.2297	-21563.5	-4952.92
36	29160.00	99.2	12941.87	0.2235	-6177.91	-1380.84	108864.00	99.2	47016.9	0.2297	-21563.5	-4952.92
37	9600.00	99.2	5101.21	0.1867	-3218.59	-600.862	42336.00	99.2	15423.44	0.2723	-5567.38	-1515.97
38	7488.00	99.2	3911.02	0.1899	-2399.67	-455.762	33768.00	99.2	12302.03	0.2723	-4440.65	-1209.16
39	5760.00	99.2	3008.48	0.1899	-1845.9	-350.586	33768.00	99.2	12302.03	0.2723	-4440.65	-1209.16

"3DOFRUB" System 12 Output File .

```
                          **** System 12 ****

                            ** Hull 616 **

                         * Ship Parameters *

    Weight          Moment of Inertia          K.G.
  16369.9 kips    2410451.0 kips-in-sec2     193.0 ins

                        * Drydock Parameters *

Side Block Height    Side Block Width    Keel Block Height    Keel Block Width
   75.0 ins               42.0 ins             61.0 ins             48.0 ins

Side-to-Side Pier Distance    Wale Shore Ht.    Wale Shore Stiffness   Cap Angle
      144.0 ins                     .0 ins                .0 kips/in   .377 rad

1Side Side Pier Contact Area    Total Keel Pier Contact Area       kkhp
           8352.0 in2                      55440.0 in2           18215.1 kips/in

B/B Friction Coeff    H/B Friction Coeff      kshp           kvsp
        .430                  .750        4583.8 kips/in  7552.4 kips/in

Side Pier Fail Stress Limit     Keel Pier Fail Stress Limit       kvkp
           .700 kips/in2                   .700 kips/in2       37857.8 kips/in

Side Pier Vertical Stiffness    Side Pier Horizontal Stiffness
       4554.2 kips/in                 4583.8 kips/in

Keel Pier Vertical Stiffness    Keel Pier Horizontal Stiffness
      25286.7 kips/in                18215.1 kips/in

     QD1                   QD2                   QD3                  QD4
      .0 kips               .0 kips            -545.4 kips          -2734.1 kips

                   * System Parameters and Inputs *

Earthquake Used is 1940 EL CENTRO

Horizontal acceleration input is HORIZONTAL

Vertical acceleration input is
                    Earthquake Acceleration Time History.

Vertical/Horizontal Ground Acceleration Ratio    Data Time Increment
          1.000                                        .010 sec

Gravitational Constant   % System Damping
       386.09 in/sec2          5.00 %

                         Mass Matrix

          42.3992               .0000          8183.0420
            .0000             42.3992              .0000
        8183.0420               .0000       2410451.0000

                        Damping Matrix

          74.3450               .0000          3428.9487
            .0000            120.7812              .0000
        3428.9487               .0000       1021727.6065
```

```
                        Stiffness Matrix
     27382.8800                 .0000          128348.1200
          .0000            34395.1400                .0000
    128346.1200                 .0000        43319122.8111


Undamped Natural Frequencies       Mode #1         Mode #2          Mode #3
                                 4.239 rad/sec 42.984 rad/sec  28.482 rad/sec
Damped Natural Frequencies         Mode #1         Mode #2          Mode #3
                                 4.233 rad/sec 42.930 rad/sec  28.448 rad/sec


For Earthquake Acceleration of 100.00 % of the 1940 EL CENTRO

Maximums/Failures          X (ins)   Y (ins)          Theta (rads)  Time (sec)
-----------------        --------  --------        ------------- ----------
 Maximum X                 .133628                                    6.70
 Maximum Y                          -.252150                          5.34
 Maximum Rotation                                     .014311         9.12
Side block sliding         .074181   .085959         -.002947         8.41
Side block overturning     .087029   .188782          .003970         5.42
Keel block overturning   -.085370    .031225         -.000848         4.91
Side block liftoff         .018785  -.025509         -.006513         5.02
Side block crushing        .018526  -.098058         -.005124         4.99


For Earthquake Acceleration of  90.00 % of the 1940 EL CENTRO

Maximums/Failures          X (ins)   Y (ins)          Theta (rads)  Time (sec)
-----------------        --------  --------        ------------- ----------
 Maximum X                 .121682                                    6.70
 Maximum Y                          -.228920                          5.34
 Maximum Rotation                                     .012817         9.12
Side block overturning     .067689   .073061         -.002638         8.41
Keel block overturning   -.087898    .010883         -.001173         4.92
Side block liftoff         .017590  -.022420         -.005890         5.02
Side block crushing       -.005126   .101402         -.008079         5.10


For Earthquake Acceleration of  80.00 % of the 1940 EL CENTRO

Maximums/Failures          X (ins)   Y (ins)          Theta (rads)  Time (sec)
-----------------        --------  --------        ------------- ----------
 Maximum X                 .110005                                    6.70
 Maximum Y                          -.202051                          5.34
 Maximum Rotation                                     .011419         9.12
Side block overturning    -.075537   .078222          .000599         8.12
Keel block overturning     .075679   .064484          .002542         5.40
Side block liftoff         .002582   .009507         -.005600         5.03
Side block crushing        .025392   .063558         -.007498         5.12


For Earthquake Acceleration of  70.00 % of the 1940 EL CENTRO

Maximums/Failures          X (ins)   Y (ins)          Theta (rads)  Time (sec)
```

```
 Maximum X               .099249                                   6.70
 Maximum Y                         -.178057                        5.34
 Maximum Rotation                                 .010018          9.11
Keel block overturning   .070214    .101565       .002562          5.41
Side block liftoff      -.007956    .033827      -.005177          5.04
Side block crushing      .055384   -.070826       .005715          5.52


For Earthquake Acceleration of  60.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------       --------  --------       -------------  ----------
 Maximum X               .084043                                   6.70
 Maximum Y                         -.153034                        5.34
 Maximum Rotation                                 .008604          9.11
Keel block overturning   .062017    .087278       .002219          5.41
Side block liftoff      -.018024    .061380      -.004807          5.06
Side block crushing      .035903   -.084247       .005279          5.54


For Earthquake Acceleration of  50.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------       --------  --------       -------------  ----------
 Maximum X               .069096                                   6.70
 Maximum Y                         -.128438                        5.34
 Maximum Rotation                                 .007234          9.10
Side block liftoff      -.037360    .030443      -.005009          6.02
Side block crushing      .010836   -.009880      -.006406          6.09


For Earthquake Acceleration of  40.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------       --------  --------       -------------  ----------
 Maximum X              -.055491                                   8.43
 Maximum Y                         -.103239                        5.34
 Maximum Rotation                                 .005911          9.08
Side block liftoff       .014700   -.021988       .005709          9.02


For Earthquake Acceleration of  30.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------       --------  --------       -------------  ----------
 Maximum X              -.043904                                   8.43
 Maximum Y                         -.073915                        5.34
 Maximum Rotation                                 .004762          9.05

No failures occurred.
```

```
For Earthquake Acceleration of  39.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------        --------  --------      -------------  ----------
 Maximum X               -.054318                                 8.43
 Maximum Y                         -.100658                       5.34
 Maximum Rotation                                  .005843        9.08
Side block liftoff        .013999  -.021378        .005664        9.02
```

```
For Earthquake Acceleration of  38.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------        --------  --------      -------------  ----------
 Maximum X               -.054144                                 8.43
 Maximum Y                         -.098077                       5.34
 Maximum Rotation                                  .005714        9.08
Side block liftoff        .015857  -.016848        .005612        9.03
```

```
For Earthquake Acceleration of  37.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------        --------  --------      -------------  ----------
 Maximum X               -.052896                                 8.43
 Maximum Y                         -.095496                       5.34
 Maximum Rotation                                  .005584        9.07
Side block liftoff        .019130  -.010292        .005538        9.04
```

```
For Earthquake Acceleration of  36.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------        --------  --------      -------------  ----------
 Maximum X               -.051656                                 8.43
 Maximum Y                         -.092694                       5.34
 Maximum Rotation                                  .005448        9.07
Side block liftoff        .021071  -.002704        .005429        9.05
```

```
For Earthquake Acceleration of  35.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------        --------  --------      -------------  ----------
 Maximum X               -.050382                                 8.43
 Maximum Y                         -.089906                       5.34
 Maximum Rotation                                  .005338        9.07
Side block liftoff        .022892   .005154        .005337        9.06
```

```
For Earthquake Acceleration of  34.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------        --------  --------      -------------  ----------
 Maximum X               -.048970                                 8.43
 Maximum Y                         -.086829                       5.34
 Maximum Rotation                                  .005216        9.06
Side block liftoff        .022342   .012550        .005214        9.07
```

```
For Earthquake Acceleration of  33.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)   Y (ins)       Theta (rads)  Time (sec)
-----------------       --------  --------      ------------- -----------
 Maximum X              -.047773                                 8.43
 Maximum Y                        -.083611                       5.34
 Maximum Rotation                                .005105         9.06
Side block liftoff        .018046   .023179      .005067         9.09


For Earthquake Acceleration of  32.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)   Y (ins)       Theta (rads)  Time (sec)
-----------------       --------  --------      ------------- -----------
 Maximum X              -.046433                                 8.43
 Maximum Y                        -.080243                       5.34
 Maximum Rotation                                .004966         9.06

No failures occurred.
```

"3DOFRUB" System 12 Input Data File

```
-16369.9 193.0 2410451 -4564.23   7552.43 [illegible]0.0      0.0
  4583.79  18215.10 -4583.79  18215.10 [illegible]00  -545.44 386.09
 42.00  48 00 -76 00 -61 00 0.43 0.78 [illegible]
  144 00 0.70 0 70   8352 0  55440.0 0 050
  616  12 0.377  -2734.11  37857.79


LAFAYETTE SSBN 616
RUBBER CAPS
8 SPACING COMPOSITE
NO WALE SHORES
5 % DAMPING
NO SPECIFIC LOCATION
845-2006640
S12KHE1.WK1 & S12SHE1.WK1 ETC.
S12RUB.DAT  18:01 30 JAN 88
```

APPENDIX 5

1. Isolator Equivalent Elastic Moduli Spreadsheets
2. Isolator Blocking Pier Stiffness Spreadsheets,
3. "3DOFRUB" System 90 Output File,
4. "3DOFRUB" System 90 Input Data File

Isolator Equivalent Elastic Moduli Spreadsheets. . . . .

DIS E CALC
SIDE BLOCKS
KU_{29} = 1780 [illegible]
E EQUIV = 726.5 [illegible]

```
     11-Jan-88

HORIZONTAL STIFFNESS MATRIX FOR 4 LAYERS        DIS E CALCULATOR FOR SIDE BLOCKS

THIS IS A SIDEBLOCK SYSTEM FOR HULL 616 WITH 5 FT BUILDUP
6 FOOT CENTERS


  ELEMENT # 1     CONCRETE
                   DEPTH       TRANSVERSE                    HEIGHT
        E1           B1            H1            I1            L1
      (PSI)         (IN)          (IN)        (IN^4)          (IN)
  --------------------------------------------------------------------

   1.0000000E+50           48            42        296352             24

  --------------------------------------------------------------------

  12E1I1/L1^3    6E1I1/L1^2     4E1I1/L1       2E1I1/L1
  --------------------------------------------------------------------

   2.5725000E+52  3.0870000E+53  4.9392000E+54  2.4696000E+54
  --------------------------------------------------------------------

     RIGIDITY         TOP          SHEAR        ELEMENT
       G1-          CONTACT        STRAIN        SHEAR
      (PSI)          AREA         (IN/IN)     DEFLECTION
                    (IN^2)                       (IN)
  --------------------------------------------------------------------

  ###############          2016  8.2671958E-51  1.3841270E-49

  --------------------------------------------------------------------


  ELEMENT # 2     OAK
                   DEPTH       TRANSVERSE                    HEIGHT
        E2           B2            H2            I2            L2
      (PSI)         (IN)          (IN)        (IN^4)          (IN)
  --------------------------------------------------------------------

   1.0000000E+50           48            42        296352             22

  --------------------------------------------------------------------

  12E2I2/L2^3    6E2I2/L2^2     4E2I2/L2       2E2I2/L2
  --------------------------------------------------------------------

   3.3398047E+52  3.6737851E+53  5.3882182E+54  2.6941091E+54
  --------------------------------------------------------------------

     RIGIDITY         TOP          SHEAR        ELEMENT
       G2-          CONTACT        STRAIN        SHEAR
      (PSI)          AREA         (IN/IN)     DEFLECTION
                    (IN^2)                       (IN)
  --------------------------------------------------------------------

###############          2016  6.9444444E-50  1.5277778E-48

--------------------------------------------------------------------
```

```
ELEMENT # 3    DOUGLAS FIR
                 DEPTH        TRANSVERSE                    HEIGHT
    E3            B3              H3            I3            L3
   (PSI)         (IN)            (IN)         (IN^4)         (IN)
-----------------------------------------------------------------------

****************            12            24         13824            22

-----------------------------------------------------------------------

12E3I3/L3^3    6E3I3/L3^2     4E3I3/L3        2E3I3/L3
-----------------------------------------------------------------------

   1.5579E+51     1.7137E+52     2.5135E+53     1.2567E+53
-----------------------------------------------------------------------

  RIGIDITY         TOP          SHEAR         ELEMENT
    G1r          CONTACT        STRAIN         SHEAR
   (PSI)          AREA         (IN/IN)      DEFLECTION
                 (IN^2)                        (IN)
---------------------------------------------------------

****************           288  4.8611111E-49  1.0694444E-47

-----------------------------------------------------------------------


ELEMENT # 4    DIS ISOLATOR
                 DEPTH        TRANSVERSE                    HEIGHT
    E4            B4              H4            I4            L3
   (PSI)         (IN)            (IN)         (IN^4)         (IN)
-----------------------------------------------------------------------

    786.50000            48            42        296352            22

-----------------------------------------------------------------------

12E4I4/L4^3    6E4I4/L4^2     4E4I4/L4        2E4I4/L4
-----------------------------------------------------------------------

   2.6268E+05     2.8894E+06     4.2378E+07     2.1189E+07
-----------------------------------------------------------------------

  RIGIDITY         TOP          SHEAR         ELEMENT
    G1r          CONTACT        STRAIN         SHEAR          TOTAL
   (PSI)          AREA         (IN/IN)      DEFLECTION        SHEAR
                 (IN^2)                        (IN)      DEFLECTION (IN)
-----------------------------------------------------------------------

         267          2016  0.0018610301  0.0409426626     4.0943E-02
```

```
F/                                            STIFFNESS MATRIX
M                                                                                                                          D


Q1   2.5725E+52   3.0870E+53  -2.5725E+52   3.0870E+53   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00 a1

M1   3.0870E+53   4.9392E+54  -3.0870E+53   2.4696E+54   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00 th1

Q2  -2.5725E+52  -3.0870E+53   5.9123E+52   5.8679E+52  -3.3398E+52   3.6738E+53   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00 a2

M2   3.0870E+53   2.4696E+54   5.8679E+52   1.0327E+55  -3.6738E+53   2.6941E+54   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00 th2

Q3   0.0000E+00   0.0000E+00  -3.3398E+52  -3.6738E+53   3.4956E+52  -3.5024E+53  -1.5579E+51   1.7137E+52   0.0000E+00   0.0000E+00 a3

M3   0.0000E+00   0.0000E+00   3.6738E+53   2.6941E+54  -3.5024E+53   5.6396E+54  -1.7137E+52   1.2567E+53   0.0000E+00   0.0000E+00 th3

Q4   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00  -1.5579E+51  -1.7137E+52   1.5579E+51  -1.7137E+52 -2.62676E+05  2.88943E+06 a4

M4   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.7137E+52   1.2567E+53  -1.7137E+52   2.5135E+53 -2.88943E+06  2.11892E+07 th4

     0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00 -2.62676E+05 -2.88943E+06  2.62676E+05 -2.88943E+06 a5

M5   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00  2.88943E+06  2.11892E+07 -2.88943E+06  4.23783E+07 th5

--------------------------------------------------------------------------------------------------------------------  -------------------------------
```

```
KNOWN VALUES:                                              # OF SYSTEM BLOCKS =                29
Q1 =                                      -1000 lbs

M1 = Q1*(L1+L2+L3+L4) =                   -90000 IN*LBS

Q2 = M2 = Q3 = M3 = M4 = Q4 = M5             0

Q5 =                                       1000 lbs

q1 = th1=                     0
----------------------------------------------------------------------------------------

SOLVED UNKNOWNS:

q2= 7.9689018E-49 in

th2 6.3168124E-50 rad
                                                                   -B1          -B2
   2.6656589E-48 in                                        -50821.187077  -699123.96694

th3 1.0339795E-49 rad
q4  1.1372402E-47 in                                        -6935.1328382 -115821.314122

th4 6.2917156E-49 rad


q5  0.0152279064 in                                                 -1000        -22000

th5  0.0010382663 rad

K (HORIZONTAL) FOR 1 KEEL BLOCK = 8.7932169E+49 lbs/in      8.7932169E+46 KIPS/IN
----------------------------------------------------------------------------------------

K (HORIZONTAL) ALL KEEL BLOCKS =  2.5500329E+51 lbs/in      2.5500329E+48 KIPS/IN
----------------------------------------------------------------------------------------

MATRIX CHECK:

  Q1 =               -1000.0000

  M1 =              -90000.0000

  Q2 =                  -0.0000

  M2 =                  -0.0000

  Q3 =                  -0.0000

  M3 =                  -0.0000

  Q4 =                   0.0000

  M4 =                   0.0000

  Q5 =                1000.0000

  M5 =                   0.0000
========================================================================================


TOTAL SIDE BLOCK HORIZONTAL STIFFNESS COEFFICIENT CALCULATION:                       .

----------------------------------------------------------------------------------------

Khs (SIDEBLOCK HORIZONTAL STIFFNESS) = P/(BENDING DISPL + SHEAR DISPLACEMENT)
                        17.8000
Khs         =            17.80 KIPS/IN        (PER BLOCK)

Khs         =           516.28 KIPS/IN        (ENTIRE SIDE BLOCK SYSTEM)
----------------------------------------------------------------------------------------
```

DIS E CALC
SIDE BLOCKS
K D_{29} = 182
E EQUIV = 805 PSI

```
     11-Jan-88

HORIZONTAL STIFFNESS MATRIX FOR 4 LAYERS        DIS E CALCULATOR FOR SIDE BLOCKS

THIS IS A SIDEBLOCK SYSTEM FOR HULL 616 WITH 5 FT BUILDUP
8 FOOT CENTERS


  ELEMENT # 1    CONCRETE
                      DEPTH        TRANSVERSE                    HEIGHT
       E1              B1              H1           I1             L1
      (PSI)           (IN)            (IN)        (IN^4)          (IN)
  ------------------------------------------------------------------------

   1.0000000E+50            48             42         296352             24

  ------------------------------------------------------------------------

  12E1I1/L1^3    6E1I1/L1^2     4E1I1/L1       2E1I1/L1
  ------------------------------------------------------------------------

   2.5725000E+52  3.0870000E+53  4.9392000E+54  2.4696000E+54
  ------------------------------------------------------------------------

     RIGIDITY          TOP           SHEAR        ELEMENT
       GIr           CONTACT         STRAIN        SHEAR
      (PSI)           AREA          (IN/IN)     DEFLECTION
                     (IN^2)                        (IN)
  ------------------------------------------------------------------------

  ****************          2016  8.2671958E-51  1.9841270E-49

  ------------------------------------------------------------------------


  ELEMENT # 2    OAK
                      DEPTH        TRANSVERSE                    HEIGHT
       E2              B2              H2           I2             L2
      (PSI)           (IN)            (IN)        (IN^4)          (IN)
  ------------------------------------------------------------------------

   1.0000000E+50            48             42         296352             22

  ------------------------------------------------------------------------

  12E2I2/L2^3    6E2I2/L2^2     4E2I2/L2       2E2I2/L2
  ------------------------------------------------------------------------

   3.3398047E+52  3.6737851E+53  5.3882182E+54  2.6941091E+54
  ------------------------------------------------------------------------

     RIGIDITY          TOP           SHEAR        ELEMENT
       GIr           CONTACT         STRAIN        SHEAR
      (PSI)           AREA          (IN/IN)     DEFLECTION
                     (IN^2)                        (IN)
  ------------------------------------------------------------------------
****************          2016  6.9444444E-50  1.5277778E-48

------------------------------------------------------------------------
```

```
ELEMENT # 3    DOUGLAS FIR
                    DEPTH        TRANSVERSE                      HEIGHT
     E3              B3              H3            I3              L3
   (PSI)            (IN)            (IN)         (IN^4)           (IN)
--------------------------------------------------------------------------

***************           12              24          13824             22

--------------------------------------------------------------------------

12E3I3/L3^3    6E3I3/L3^2     4E3I3/L3       2E3I3/L3
--------------------------------------------------------------------------

   1.5579E+51     1.7137E+52     2.5135E+53     1.2567E+53
--------------------------------------------------------------------------

  RIGIDITY         TOP           SHEAR        ELEMENT
    Glr          CONTACT        STRAIN         SHEAR
   (PSI)           AREA         (IN/IN)      DEFLECTION
                 (IN^2)                        (IN)
-----------------------------------------------------------

***************            288  4.8611111E-49  1.0694444E-47

--------------------------------------------------------------------------


ELEMENT # 4    DIS ISOLATOR
                    DEPTH        TRANSVERSE                      HEIGHT
     E4              B4              H4            I4              L3
   (PSI)            (IN)            (IN)         (IN^4)           (IN)
--------------------------------------------------------------------------

    80.50000              48              42         296352             22

--------------------------------------------------------------------------

12E4I4/L4^3    6E4I4/L4^2     4E4I4/L4       2E4I4/L4
--------------------------------------------------------------------------

   2.6885E+04     2.9574E+05     4.3375E+06     2.1688E+06
--------------------------------------------------------------------------

  RIGIDITY         TOP           SHEAR        ELEMENT
    Glr          CONTACT        STRAIN         SHEAR           TOTAL
   (PSI)           AREA         (IN/IN)      DEFLECTION        SHEAR
                 (IN^2)                        (IN)      DEFLECTION (IN)
--------------------------------------------------------------------------

          27          2016    0.018182611   0.4000174422     4.0002E-01
```

```
F/                                     STIFFNESS MATRIX
M                                                                                                                                  D


Q1    2.5725E+52   3.0870E+53  -2.5725E+52   3.0870E+53   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00 q1

M1    3.0870E+53   4.9392E+54  -3.0870E+53   2.4696E+54   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00 th1

Q2   -2.5725E+52  -3.0870E+53   5.9123E+52   5.8679E+52  -3.3398E+52   3.6738E+53   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00 q2

M2    3.0870E+53   2.4696E+54   5.8679E+52   1.0327E+55  -3.6738E+53   2.6941E+54   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00 th2

Q3    0.0000E+00   0.0000E+00  -3.3398E+52  -3.6738E+53   3.4956E+52  -3.5024E+53  -1.5579E+51   1.7137E+52   0.0000E+00   0.0000E+00 q3

M3    0.0000E+00   0.0000E+00   3.6738E+53   2.6941E+54  -3.5024E+53   5.6396E+54  -1.7137E+52   1.2567E+53   0.0000E+00   0.0000E+00 th3

Q4    0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00  -1.5579E+51  -1.7137E+52   1.5579E+51  -1.7137E+52 -2.68854E+04  2.95740E+05 q4

M4    0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.7137E+52   1.2567E+53  -1.7137E+52   2.5135E+53 -2.95740E+05  2.16876E+06 th4

      0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00 -2.68854E+04 -2.95740E+05  2.68854E+04 -2.95740E+05 q5

M5    0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00  2.95740E+05  2.16876E+06 -2.95740E+05  4.33752E+06 th5

--------------------------------------------------------------------------------------------------------------------------------------
```

```
KNOWN VALUES:                                                  # OF SYSTEM BLOCKS =                  29
Q1 =                              -1000 lbs

M1 = Q1*(L1+L2+L3+L4) =          -90000 IN*LBS

Q2 = M2 = Q3 = M3 = M4 = Q4 = M5      0

Q5 =                               1000 lbs

q1 = th1=                 0
------------------------------------------------------------------------------------------

SOLVED UNKNOWNS:

q2= 7.9689018E-49 in

th2 6.3168124E-50 rac

                                                                  -B1            -B2
   2.66565895E-48 in                                         -50821.187077  -695123.96694

th3 1.03997956E-49 rad
q4 1.13724025E-47 in                                         -6935.1328382 -115821.314122

th4 6.29171566E-49 rad


q5   0.1487794329 in                                               --1000         -22000

th5  0.0101440557 rad

K (HORIZONTAL) FOR 1 KEEL BLOCK = 8.7932169E+49 lbs/in        8.7932169E+46 KIPS/IN
------------------------------------------------------------------------------------------

K (HORIZONTAL) ALL KEEL BLOCKS =  2.5500329E+51 lbs/in        2.5500329E+48 KIPS/IN
------------------------------------------------------------------------------------------

MATRIX CHECK:

  Q1 =            -1000.0000

  M1 =           -90000.0000

  Q2 =               -0.0000

  M2 =               -0.0000

  Q3 =               -0.0000

  M3 =               -0.0000

  Q4 =                0.0000

  M4 =               -0.0000

  Q5 =             1000.0000

  M5 =               -0.0000
==========================================================================================


TOTAL SIDE BLOCK HORIZONTAL STIFFNESS COEFFICIENT CALCULATION:

------------------------------------------------------------------------------------------

Khs (SIDEBLOCK HORIZONTAL STIFFNESS) = P/(BENDING DISPL + SHEAR DISPLACEMENT)
                                1.8280
Khs       =                 1.82 KIPS/IN        (PER BLOCK)

Khs       =                52.34 KIPS/IN        (ENTIRE SIDE BLOCK SYSTEM)
----------------------------------------            ------------------------------
```

~~DIS E CALCULATOR FOR KEEL BLOCKS SUBSTITUTING THE I [illegible] IN FOR ELEMENT 4 AND MAKING ALL OTHER LAYER E = 1000. KU_{55} = 31.31 KIPS/IN.~~

EQUIVALENT E = 1567 PSI

```
       11-Jan-88

HORIZONTAL STIFFNESS MATRIX FOR 4 LAYERS        DIS E CALCULATOR

THIS IS A KEEL SYSTEM FOR HULL 616 WITH 5 FT BUILDUP
8 FOOT CENTERS


 ELEMENT # 1    CONCRETE
                    DEPTH        TRANSVERSE                      HEIGHT
      E1             B1             H1             I1             L1
     (PSI)          (IN)           (IN)          (IN^4)          (IN)
 ----------------------------------------------------------------------

  1.0000000E+50            42            48         387072           27

 ----------------------------------------------------------------------

 12E1I1/L1^3    6E1I1/L1^2     4E1I1/L1       2E1I1/L1
 ----------------------------------------------------------------------

  2.3598354E+52  3.1857778E+53  5.7344000E+54  2.8672000E+54
 ----------------------------------------------------------------------

    RIGIDITY          TOP          SHEAR        ELEMENT
      Gir           CONTACT        STRAIN        SHEAR
     (PSI)           AREA         (IN/IN)      DEFLECTION
                    (IN^2)                        (IN)
 ----------------------------------------------------------------------

 ****************          2016  8.2671958E-51  2.2321429E-49

 ----------------------------------------------------------------------


 ELEMENT # 2    OAK
                    DEPTH        TRANSVERSE                      HEIGHT
      E2             B2             H2             I2             L2
     (PSI)          (IN)           (IN)          (IN^4)          (IN)
 ----------------------------------------------------------------------

  1.0000000E+50            42            48         387072           29

 ----------------------------------------------------------------------

 12E2I2/L2^3    6E2I2/L2^2     4E2I2/L2       2E2I2/L2
 ----------------------------------------------------------------------

  1.9044914E+52  2.7615125E+53  5.3389241E+54  2.6694621E+54
 ----------------------------------------------------------------------

    RIGIDITY          TOP          SHEAR        ELEMENT
      Gir           CONTACT        STRAIN        SHEAR
     (PSI)           AREA         (IN/IN)      DEFLECTION
                    (IN^2)                        (IN)
 ----------------------------------------------------------------------
****************          2016  6.9444444E-50  2.0138889E-48

----------------------------------------------------------------------
```

```
ELEMENT # 3    DOUGLAS FIR
                  DEPTH        TRANSVERSE                   HEIGHT
     E3            B3             H3            I3            L3
    (PSI)         (IN)           (IN)         (IN^4)         (IN)
-------------------------------------------------------------------

***************            42            48       387072          4

-------------------------------------------------------------------

12E3I3/L3^3    6E3I3/L3^2    4E3I3/L3       2E3I3/L3
-------------------------------------------------------------------

   7.2576E+54    1.4515E+55    3.8707E+55    1.9354E+55
-------------------------------------------------------------------

  RIGIDITY        TOP          SHEAR         ELEMENT
    Gir         CONTACT        STRAIN         SHEAR
   (PSI)         AREA         (IN/IN)      DEFLECTION
                (IN^2                          (IN)
-----------------------------------------------------

***************          2016  6.9444444E-50  2.7777778E-49

-------------------------------------------------------------------


ELEMENT # 4    ~~(60 RUBBER (PAGE 27), (SELVADURAI & MOUTAFIS, 1981))~~ OIS ISOLATORS
                  DEPTH        TRANSVERSE                   HEIGHT
     E4            B4             H4            I4            L3
    (PSI)         (IN)           (IN)         (IN^4)         (IN)
-------------------------------------------------------------------

   1567.00000          42            48       387072         25

-------------------------------------------------------------------

12E4I4/L4^3    6E4I4/L4^2    4E4I4/L4       2E4I4/L4
-------------------------------------------------------------------

   4.6582E+05    5.8229E+06    9.7047E+07    4.8523E+07
-------------------------------------------------------------------

  RIGIDITY        TOP          SHEAR         ELEMENT
    Gir         CONTACT        STRAIN         SHEAR         TOTAL
   (PSI)         AREA         (IN/IN)      DEFLECTION       SHEAR
                (IN^2                          (IN)     DEFLECTION (IN)
-------------------------------------------------------------------

         531          2016   0.000934078  0.0233513494    2.3352E-02
```

```
KNOWN VALUES:                                          # OF SYSTEM BLOCKS =              29
Q1 =                                  -1000 lbs

M1 = Q1*(L1+L2+L3+L4) =               -85000 IN*LBS

Q2 = M2 = Q3 = M3 = M4 = Q4 = M5          0

Q5 =                                   1000 lbs

d1 = th1=                  0
-------------------------------------------------------------------------------

SOLVED UNKNOWNS:

d2= 7.1568080E-49 in

th2 4.9874442E-50 rad
                                                            -B1          -B2
   2.6871142E-48 in                                   -28402.968551 -521912.00951

th3 8.2465278E-50 rad

q4  3.0226935E-48 in                                      -20700000     -42225000

th4 8.5255456E-50 rad


d5   0.0085869431 in                                          -1000        -25000

th5  0.0005152159 rad

K (HORIZONTAL) FOR 1 KEEL BLOCK = 3.3083077E+50 lbs/in      3.3083077E+47 KIPS/IN
-------------------------------------------------------------------------------

K (HORIZONTAL) ALL KEEL BLOCKS =  9.5940923E+51 lbs/in      9.5940923E+48 KIPS/IN
-------------------------------------------------------------------------------

MATRIX CHECK:

  Q1 =             -1000.0000

  M1 =            -85000.0000

  Q2 =                -0.0000

  M2 =                -0.0000

  Q3 =                -0.0000

  M3 =                -0.0000

  Q4 =                -0.0052

  M4 =                -0.0654

  Q5 =              1000.0052

  M5 =                -0.0654
===============================================================================


TOTAL KEEL BLOCK HORIZONTAL STIFFNESS COEFFICIENT CALCULATION:

-------------------------------------------------------------------------------

Khs (KEEL BLOCK HORIZONTAL STIFFNESS) = P/(BENDING DISPL + SHEAR DISPLACEMENT)
                          31.3100
Khs        =               31.31 KIPS/IN        (PER BLOCK)

Khs        =              907.98 KIPS/IN        (ENTIRE KEEL BLOCK SYSTEM)
-------------------------------------------------------------------------------
```

~~USE E CALC~~
~~FOR KEEL BLOCK~~
~~KD55 = 2.72~~
~~E EQUIV = 26[illegible]~~

```
      11-Jan-88

HORIZONTAL STIFFNESS MATRIX FOR 4 LAYERS        DIS E CALCULATOR

THIS IS A KEEL SYSTEM FOR HULL 616 WITH 5 FT BUILDUP
6 FOOT CENTERS


   ELEMENT # 1     CONCRETE
                       DEPTH        TRANSVERSE                      HEIGHT
        E1              B1              H1            I1              L1
       (PSI)           (IN)            (IN)         (IN^4)           (IN)
   -------------------------------------------------------------------------

    1.0000000E+50             42              48        387072              27

   -------------------------------------------------------------------------

   12EI1/L1^3     6EI1/L1^2      4EI1/L1       2EI1/L1
   -------------------------------------------------------------------------

    2.3598354E+52  3.1857778E+53  5.7344000E+54  2.8672000E+54
   -------------------------------------------------------------------------

      RIGIDITY           TOP           SHEAR        ELEMENT
        Glr            CONTACT         STRAIN        SHEAR
       (PSI)            AREA          (IN/IN)      DEFLECTION
                       (IN^2)                         (IN)
   -------------------------------------------------------------------------

   ***************           2016  8.2671958E-51  2.2321429E-49

   -------------------------------------------------------------------------


   ELEMENT # 2     OAK
                       DEPTH        TRANSVERSE                      HEIGHT
        E2              B2              H2            I2              L2
       (PSI)           (IN)            (IN)         (IN^4)           (IN)
   -------------------------------------------------------------------------

    1.0000000E+50             42              48        387072              29

   -------------------------------------------------------------------------

   12EI2/L2^3     6EI2/L2^2      4EI2/L2       2EI2/L2
   -------------------------------------------------------------------------

    1.9044914E+52  2.7615125E+53  5.3389241E+54  2.6694621E+54
   -------------------------------------------------------------------------

      RIGIDITY           TOP           SHEAR        ELEMENT
        Glr            CONTACT         STRAIN        SHEAR
       (PSI)            AREA          (IN/IN)      DEFLECTION
                       (IN 2                          (IN)
                                                  ----------------------
***************           2016  6.9444444E-50  2.0138889E-48

------------------------------------------------------------------------
```

```
ELEMENT # 3    DOUGLAS FIR
                 DEPTH       TRANSVERSE                  HEIGHT
     E3           B3            H3           I3            L3
   (PSI)         (IN)          (IN.        (IN^4)         (IN)
--------------------------------------------------------------------

****************       42            48        387072            4

--------------------------------------------------------------------

12E3I3/L3^3   6E3I3/L3^2    4E3I3/L3      2E3I3/L3
--------------------------------------------------------------------

   7.2576E+54    1.4515E+55    3.8707E+55    1.9354E+55
--------------------------------------------------------------------

  RIGIDITY        TOP          SHEAR        ELEMENT
    G1r         CONTACT        STRAIN        SHEAR
   (PSI)         AREA         (IN/IN)     DEFLECTION
                (IN^2)                       (IN)
-------------------------------------------------------

****************     2016  6.9444444E-50  2.7777778E-49

--------------------------------------------------------------------

               DIS   ISOLATORS
ELEMENT # 4    ~~AFI RUBBER PAGE 271, (SELVADURAI & MOUTAFIS, 1981))~~
                 DEPTH       TRANSVERSE                  HEIGHT
     E4           B4            H4           I4            L3
   (PSI)         (IN)          (IN)        (IN^4)         (IN)
--------------------------------------------------------------------

   186.00000           42            48        387072           25

--------------------------------------------------------------------

12E4I4/L4^3   6E4I4/L4^2    4E4I4/L4      2E4I4/L4
--------------------------------------------------------------------

   5.5292E+04    6.9116E+05    1.1519E+07    5.7596E+06
--------------------------------------------------------------------

  RIGIDITY        TOP          SHEAR        ELEMENT
    G1r         CONTACT        STRAIN        SHEAR         TOTAL
   (PSI)         AREA         (IN/IN)     DEFLECTION       SHEAR
                (IN 2)                       (IN)     DEFLECTION (IN)
--------------------------------------------------------------------

          63         2016   0.0078693558   0.196733896     1.9673E-01
```

```
F/                                  STIFFNESS MATRIX
M                                                                                                                          D



Q1    2.3596E+52   3.1858E+53  -2.3598E+52   3.1858E+53   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00 a1

M1    3.1858E+53   5.7344E+54  -3.1858E+53   2.8672E+54   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00 th1

Q2   -2.3598E+52  -3.1858E+53   4.2643E+52  -4.2427E+52  -1.9045E+52   2.7615E+53   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00 a2

M2    3.1858E+53   2.8672E+54  -4.2427E+52   1.1073E+55  -2.7615E+53   2.6695E+54   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00 th2

Q3    0.0000E+00   0.0000E+00  -1.9045E+52  -2.7615E+53   7.2766E+54   1.4239E+55  -7.2576E+54   1.4515E+55   0.0000E+00   0.0000E+00 a3

M3    0.0000E+00   0.0000E+00   2.7615E+53   2.6695E+54   1.4239E+55   4.4046E+55  -1.4515E+55   1.9354E+55   0.0000E+00   0.0000E+00 th3

Q4    0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00  -7.2576E+54  -1.4515E+55   7.2576E+54  -1.4515E+55 -5.52925E+04  6.91156E+05 a4

M4    0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.4515E+55   1.9354E+55  -1.4515E+55   3.8707E+55 -6.91156E+05  5.75963E+06 th4

      0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00 -5.52925E+04 -6.91156E+05  5.52925E+04 -6.91156E+05 a5

M5    0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00  6.91156E+05  5.75963E+06 -6.91156E+05  1.15193E+07 th5

------------------------------------------------------------------------------------------------------------------------------------
```

```
KNOWN VALUES:                                                   # OF SYSTEM BLOCKS =            29
Q1 =                                        -1000 lbs

M1 = Q1*(L1+L2+L3+L4) =                    -85000 IN*LBS

Q2 = M2 = Q3 = M3 = M4 = Q4 = M5               0

Q5 =                                         1000 lbs

q1 = th1=                      0
--------------------------------------------------------------------------------

SOLVED UNKNOWNS:

q2= 7.1568080E-49 in

th2 4.9874442E-50 rad

                                                                  -B1           -B2
   2.6871142E-48 in                                          -28402.962551  -521912.00951

th3 8.2465278E-50 rad

q4  3.0226335E-48 in                                           -20700000      -42225000

th4 8.5255456E-50 rad


q5   0.0723425929 in                                              -1000         -25000

th5  0.0043405556 rad

K (HORIZONTAL) FOR 1 KEEL BLOCK = 3.3083077E+50 lbs/in        3.3083077E+47 KIPS/IN
--------------------------------------------------------------------------------

K (HORIZONTAL) ALL KEEL BLOCKS =  9.5940923E+51 lbs/in        9.5940923E+48 KIPS/IN
--------------------------------------------------------------------------------

MATRIX CHECK:

  Q1 =              -1000.0000

  M1 =             -85000.0000

  Q2 =                 -0.0000

  M2 =                 -0.0000

  Q3 =                 -0.0000

  M3 =                 -0.0000

  Q4 =                 -0.0000

  M4 =                 -0.0000

  Q5 =               1000.0000

  M5 =                 -0.0000
================================================================================


TOTAL KEEL BLOCK HORIZONTAL STIFFNESS COEFFICIENT CALCULATION:

--------------------------------------------------------------------------------

Khs (KEEL BLOCK HORIZONTAL STIFFNESS) = P/(BENDING DISPL + SHEAR DISPLACEMENT)
                          3.7200
Khs       =                 3.72 KIPS/IN         (PER BLOCK)

Khs       =               107.78 KIPS/IN         (ENTIRE KEEL BLOCK SYSTEM)
--------------------------------------------------------------------------------
```

Isolator Blocking Pier Stiffness Spreadsheets. . . . .

VERTICAL STIFFNESS CALCULATIONS FOR DRYDOCK BLOCKS

HULL TYPE 616 DOCKING PLAN # = 845-2006640

SYSTEM # 90 E1 KEEL BLOCKS ORIGINAL PER DOCKING PLAN

OAK REMOVED ISOLATORS INSTALLED

BLOCK SPA 8.00 FEET

VERTICAL STIFFNESS:

LEVEL #	MATERIAL	E (PSI)	LENGTH (IN) (DEPTH) (B)	WIDTH (IN) (TRANSVERSE) (H)	HEIGHT (IN) (L)	K (KIPS IN	1/K	PIER TOTAL K (KIPS/IN
1	D.FUR	12539.19	42.00	24.00	2.00	6319.75	0.0001582	1159.99
2	D.FUR	12539.19	42.00	24.00	2.00	6319.75	0.0001582	
3	DIS		42.00	48.00	25.00	1845.[illegible]	0.00054[illegible]	
4	CONCRETE	4000000.00	42.00	48.00	31.00	260129.03	0.0000038	

1845.[illegible]

# BLOCKS	55	TOTAL STIF OF BLOCK SY (KIPS/IN) :
		63799.62

```
VERTICAL STIFFNESS CALCULATIONS

HULL TYPE   616    DOCKING PLAN # =    845-2006640

SYSTEM # 90 E1              SIDE BLOCKS          ORIGINAL PER DOCKING DRAWING
                                                 OAK REMOVED ISOLATORS INSTALLED
BLOCK SPACING =          8.00 FEET

VERTICAL STIFFNESS:
_____________________________________________________________________________________
                                                                                PIER
 LEVEL  MATERIAL      E      LENGTH      WIDTH      HEIGHT        K         I/K      TOTAL K
   #                (PSI)     (IN)        (IN)       (IN)     (KIPS/IN)            (KIPS/IN)
_____________________________________________________________________________________
                            (DEPTH) (TRANSVERSE)
                              (B)        (H)         (L)


   1     D.FIR    12539.19    12.00      24.00       3.00      1203.76    0.0008307   351.66
   2     D.FIR    12539.19    12.00      24.00       3.00      1203.76    0.0008307
   3      DIS                 48.00      42.00      22.00       850.00    0.0011765
   4    CONCRETE 4000000.00   48.00      42.00      46.00    175304.35    0.0000057


                    850.00                         #                              TOTAL STIFF
                                                 BLOCKS             29            OF BLOCK SY
                                                                                  (KIPS/IN):

                                                                                  10198.22
```

```
VERTICAL STIFFNESS CALCULATIONS

HULL TYPE   616    DOCKING PLAN # =    845-2006640

SYSTEM # 90 E2              SIDE BLOCKS          ORIGINAL PER DOCKING DRAWING
                                                 OAK REMOVED ISOLATORS INSTALLED
BLOCK SPACING =          8.00 FEET

VERTICAL STIFFNESS:
_____________________________________________________________________________________
                                                                                PIER
 LEVEL  MATERIAL      E      LENGTH      WIDTH      HEIGHT        K         I/K      TOTAL K
   #                (PSI)     (IN)        (IN)       (IN)     (KIPS/IN)            (KIPS/IN)
_____________________________________________________________________________________
                            (DEPTH) (TRANSVERSE)
                              (B)        (H)         (L)


   1     D.FIR     3473.50    12.00      24.00       3.00       333.46    0.0029989   139.28
   2     D.FIR     3473.50    12.00      24.00       3.00       333.46    0.0029989
   3      DIS                 48.00      42.00      22.00       850.00    0.0011765
   4    CONCRETE 4000000.00   48.00      42.00      46.00    175304.35    0.0000057


                    850.00                         #                              TOTAL STIFF
                                                 BLOCKS             29            OF BLOCK SY
                                                                                  (KIPS/IN):

                                                                                  4039.02
```

```
===========================================================================

TOTAL SIDE BLOCK HORIZONTAL STIFFNESS COEFFICIENT CALCULATION:
SYSTEM 90 E1
-----------------    --

Khs (SIDEBLOCK HORIZONTAL STIFFNESS) = P/(BENDING DISPL + SHEAR DISPLACEMENT)

Khs       =                  4.30 KIPS/IN       (PER BLOCK)

Khs       =                124.71 KIPS/IN       (ENTIRE SIDE BLOCK SYSTEM)
--------------------------------------  -------  -  --  -

===========================================================================

TOTAL SIDE BLOCK HORIZONTAL STIFFNESS COEFFICIENT CALCULATION:
SYSTEM 90 E2
---------------------------------------------------------------------------

Khs (SIDEBLOCK HORIZONTAL STIFFNESS) = P/(BENDING DISPL + SHEAR DISPLACEMENT)

Khs       =                  0.45 KIPS/IN       (PER BLOCK)

Khs       =                 12.93 KIPS/IN       (ENTIRE SIDE BLOCK SYSTEM)
---------------------------------------------------------------------------

=============    ---

TOTAL KEEL BLOCK HORIZONTAL STIFFNESS COEFFICIENT CALCULATION:
SYSTEM 90 E1
------------  -----

Khk (KEEL BLOCK HORIZONTAL STIFFNESS) = P/(BENDING DISPL + SHEAR DISPLACEMENT)

Khk       =                 10.78 KIPS/IN       (PER BLOCK)

Khk       =                593.02 KIPS/IN       (ENTIRE KEEL BLOCK SYSTEM)
--------------------  - ---

=====================================================================---

TOTAL KEEL BLOCK HORIZONTAL STIFFNESS COEFFICIENT CALCULATION:
SYSTEM 90 E2
----------------------          --

Khk (KEEL BLOCK HORIZONTAL STIFFNESS) = P/(BENDING DISPL + SHEAR DISPLACEMENT)

Khk       =                  1.28 KIPS/IN       (PER BLOCK)

Khk       =                 70.55 KIPS/IN       (ENTIRE KEEL BLOCK SYSTEM)
-----------------------------------------------  -----    ---    -  --
```

```
               "3DOFRUB" System 90 Output File . .

                         **** System 90 ****

                           ** Hull 616 **

                         * Ship Parameters *

   Weight          Moment of Inertia        K.G.
 16369.9 kips   2410451.0 kips-in-sec2    193.0 ins


                       * Drydock Parameters *

Side Block Height   Side Block Width   Keel Block Height   Keel Block Width
   74.0 ins            999.0 ins           60.0 ins            999.0 ins

Side-to-Side Pier Distance   Wale Shore Ht.   Wale Shore Stiffness  Cap Angle
      144.0 ins                    .0 ins               .0 kips/in  .377 rad

1Side Side Pier Contact Area   Total Keel Pier Contact Area       kkhp
           8352.0 in2                   55440.0 in2               70.6 kips/in

B/B Friction Coeff   H/B Friction Coeff     kshp          kvsp
      9.000                 .530          12.9 kips/in  4039.0 kips/in

Side Pier Fail Stress Limit    Keel Pier Fail Stress Limit      kvkp
           .700 kips/in2                 .700 kips/in2       63799.6 kips/in

Side Pier Vertical Stiffness   Side Pier Horizontal Stiffness
      10198.2 kips/in                  124.7 kips/in

Keel Pier Vertical Stiffness   Keel Pier Horizontal Stiffness
      63799.6 kips/in                  593.0 kips/in

    QD1                   QD2                  QD3                  QD4
  606.4 kips           132.0 kips          2269.9 kips             .0 kips

                  * System Parameters and Inputs *

Earthquake Used is 1940 EL CENTRO

Horizontal acceleration input is HORIZONTAL

Vertical acceleration input is
                     Earthquake Acceleration Time History.

Vertical/Horizontal Ground Acceleration Ratio   Data Time Increment
         1.000                                         .010 sec

Gravitational Constant   % System Damping
      386.09 in/sec2            8.00 %

                         Mass Matrix

         42.3992               .0000          8183.0420
           .0000             42.3992             .0000
       8183.0420               .0000       2410451.0000

                        Damping Matrix

         28.1828               .0000          3904.7339
           .0000            302.3045             .0000
       3904.7339               .0000       2110934.2033
```

```
                        Stiffness Matrix

        842.4400               .0000            3491.8800
           .0000          84196.0600               .0000
       3491.8800               .0000       100635346.7016


Undamped Natural Frequencies      Mode #1        Mode #2         Mode #3
                                3.850 rad/sec 12.738 rad/sec  44.562 rad/sec
Damped Natural Frequencies        Mode #1        Mode #2         Mode #3
                                3.838 rad/sec 12.697 rad/sec  44.419 rad/sec


For Earthquake Acceleration of 100.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------       --------  --------       ------------- -----------
 Maximum X             15.016106                                  9.99
 Maximum Y                        -.116897                        5.32
 Maximum Rotation                                   .040585      19.89
Side block liftoff        .636733  -.007390         .003087       4.97
Side block crushing      4.559550   .028592         .010071       7.73


For Earthquake Acceleration of  90.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------       --------  --------       ------------- -----------
 Maximum X             13.527006                                  9.99
 Maximum Y                        -.107915                        5.32
 Maximum Rotation                                   .039428      19.95
Side block sliding     -5.560400  -.030395          .000234       8.40
Side block overturning -5.560400  -.030395          .000234       8.40
Side block liftoff        .212407   .017846         .002485       4.99
Side block crushing      3.317758   .022864         .010455       7.76


For Earthquake Acceleration of  80.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------       --------  --------       ------------- -----------
 Maximum X             10.686809                                 12.17
 Maximum Y                        -.096222                        5.32
 Maximum Rotation                                   .041311      15.30
Side block sliding        .775303  -.012193        -.004976      17.89
Side block overturning    .775303  -.012193        -.004976      17.89
Side block liftoff       -.605223   .049976        -.002010       5.24
Side block crushing      1.506716  -.010418         .009568       7.83


For Earthquake Acceleration of  70.00 % of the 1940 EL CENTRO

Maximums/Failures        X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------       --------  --------       ------------- -----------
 Maximum X             10.709546                                 15.88
 Maximum Y                        -.083638                        5.32

Side block liftoff       -.846694   .048686        -.002106       5.15
Side block crushing      3.066522   .002094         .009860       9.87
```

```
For Earthquake Acceleration of  60.00 % of the 1940 EL CENTRO

Maximums/Failures       X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------      --------  --------       -------------  -----------
 Maximum X             *********                               18.08
 Maximum Y                       -.072901                       5.32
 Maximum Rotation                               -.041717       18.43
Side block liftoff      -.740307   .038385       -.002281       5.13
Side block crushing     2.188692  -.003398        .009913       9.81


For Earthquake Acceleration of  50.00 % of the 1940 EL CENTRO

Maximums/Failures       X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------      --------  --------       -------------  -----------
 Maximum X             10.189670                               19.72
 Maximum Y                       -.058069                       5.32
 Maximum Rotation                               -.041047       18.32
Side block sliding       .805700   .007265       -.002592       9.04
Side block overturning   .805700   .007265       -.002580       9.04
Side block liftoff      -.618767   .033610       -.002247       5.16
Side block crushing      .074574   .002589        .009661       9.89


For Earthquake Acceleration of  40.00 % of the 1940 EL CENTRO

Maximums/Failures       X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------      --------  --------       -------------  -----------
 Maximum X             10.560604                               18.35
 Maximum Y                       -.046455                       5.32
 Maximum Rotation                               -.019585       19.51
Side block liftoff      -.974492   .021782       -.002440       8.50
Side block crushing     2.984180  -.010294        .009788      13.82


For Earthquake Acceleration of  30.00 % of the 1940 EL CENTRO

Maximums/Failures       X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------      --------  --------       -------------  -----------
 Maximum X               .929978                                9.29
 Maximum Y                       -.034841                       5.32
 Maximum Rotation                                .001783        9.20

No failures occurred.
```

```
 For Earthquake Acceleration of  39.00 % of the 1940 EL CENTRO

 Maximums/Failures         X (ins)   Y (ins)        Theta (rads)  Time (sec)
 -----------------         --- ---- ---------       --            
  Maximum X               11.118843                               18.43

 [illegible]                         [illegible]                  [illegible]
 Maximum Rotation                                    .020861      18.67
Side block liftoff          .845572  -.002007        .002686       9.65
Side block crushing        -.824612  -.007999       -.009504      12.50


For Earthquake Acceleration of  38.00 % of the 1940 EL CENTRO

Maximums/Failures          X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------         --------  --------       -------------  ----------
 Maximum X               10.650565                                19.12
 Maximum Y                           -.044132                      5.32
 Maximum Rotation                                    .041563      19.46
Side block sliding       -2.550709   -.010928       -.004957      15.09
Side block overturning   -2.550709   -.010928       -.004957      15.09
Side block liftoff          .408778  -.000005        .002816       9.69
Side block crushing        1.821167  -.009694        .010243      13.82


For Earthquake Acceleration of  37.00 % of the 1940 EL CENTRO

Maximums/Failures          X (ins)   Y (ins)        Theta (rads)  Time (sec)
-----------------         --------  --------       --
 Maximum X                1.146910                                 9.29
 Maximum Y                           -.042971                      5.32
 Maximum Rotation                                    .002199       9.20

No failures occurred.
```

"3DOFRUB" System 90 Input Data File

```
***SHIP/SUB DRYDOCK BLOCKING SYSTEM***  DATA FILE: B:S90ISO.DAT

        ***INPUT FILE DATA***


SHIP NAME:   LAFAYETTE SSBN 616
DISCRIPTION OF ISOLATORS IF USED: BILINEAR WOOD W/ ISOLATORS
DISCRIPTION OF BUILDUP: 8 SPACING COMPOSITE
DISCRIPTION OF WALE SHORES USED: NO WALE SHORES
DISCRIPTION OF DAMPING: 8 % DAMPING
LOCATION OF DRYDOCK BEING STUDIED: NO SPECIFIC LOCATION
NAVSEA DOCKING DRAWING NUMBER: 845-2006640
REFERENCE SPREADSHEET STIFFNESS CALC FILE NAME: S1KHORIG.WK1 & S1SHORIG.WK1
MISC. COMMENTS: S90ISO.DAT  1356 4 MAR 88

SHIP WEIGHT  (KIPS)                                      W= 16369.9
HEIGHT OF KG (IN)                                        H= 193
MOMENT OF INERTIA  (KIPS*IN*SEC^2)                      Ik= 2410451
SIDE PIER VERTICAL STIFFNESS (KIPS/IN)                 Kvs= 10198.22
SIDE PIER VERTICAL PLASTIC STIFFNESS (KIPS/IN)        Kvsp= 4039.02
KEEL PIER VERTICAL STIFFNESS (KIPS/IN)                 KVK= 63799.62
KEEL PIER VERTICAL PLASTIC STIFFNESS(KIPS/IN)         KVKP= 63799.62
HEIGHT OF WALE SHORES  (IN)                            AAA= 0
WALE SHORE STIFFNESS (KIPS/IN)                          KS= 0
SIDE PIER HORIZONTAL STIFFNESS (KIPS/IN)               KHS= 124.71
KEEL PIER HORIZONTAL STIFFNESS (KIPS/IN)               KHK= 593.02
SIDE PIER HORIZONTAL PLASTIC STIFFNESS(KIPS/IN)       KSHP= 12.93
KEEL PIER HORIZONTAL PLASTIC STIFFNESS(KIPS/IN)       KKHP= 70.55
RESTORING FORCE AT 0 DEFLECT KEEL HORIZ   (KIPS)       QD1= 606.41
RESTORING FORCE AT 0 DEFLECT SIDE HORIZ   (KIPS)       QD2= 132
RESTORING FORCE AT 0 DEFLECT SIDE VERT    (KIPS)       QD3= 2269.88
RESTORING FORCE AT 0 DEFLECT KEEL VERT    (KIPS)       QD4= 0
GRAVITATIONAL CONSTANT (IN/SEC^2)                     GRAV= 386.09

SIDE BLOCK WIDTH  (IN)                                 SBW= 999
KEEL BLOCK WIDTH  (IN)                                 KBW= 999
SIDE BLOCK HEIGHT (IN)                                 SBH= 74
KEEL BLOCK HEIGHT (IN)                                 KBH= 60
BLOCK ON BLOCK FRICTION COEFFICIENT                     U1= 9
HULL ON BLOCK FRICTION COEFFICIENT                      U2= .58
SIDE PIER TO SIDE PIER TRANSVERSE DISTANCE (IN)         BR= 144
SIDE PIER CAP PROPORTIONAL LIMIT                      SCPL= .7
KEEL PIER CAP PROPORTIONAL LIMIT                      KCPL= .7
TOTAL SIDE PIER CONTACT AREA (ONE SIDE) (IN^2)       SAREA= [illegible]
TOTAL KEEL PIER CONTACT AREA   (IN^2)                KAREA= 55440
PERCENT CRITICAL DAMPING                              ZETA= .08
HULL NUMBER (XXXX)                                    HULL= 616
SYSTEM NUMBER (XXX)                                   NSYS= 90
CAP ANGLE (RAD)                                       BETA= .377
```

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Thesis
H483
c.1

Hepburn
Non-linear material three degree of freedom analysis of submarine dry-dock blocking systems.

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Non-linear material three degree of freedom analysis of submarine dry-dock blocking systems.

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